Comparative study of low-emission building solutions: case studies from Norway, Portugal and Czechia and their transferability to other climates

Veronika Wenkeová

Thesis to obtain the Master of Science Degree in

Civil Engineering

Supervisor(s):   Prof. José Dinis Silvestre
                                     Prof. Freja Nygaard Rasmussen

Examination Committee

Chairperson: Prof. Augusto Martins Gomes
Supervisor: Prof. José Dinis Silvestre
Member of the Committee: Prof. Daniel Aelenei

October 2025

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Acknowledgments

Abstract

The construction sector accounts for 33% of global greenhouse gas emissions. To support European decarbonisation goals, the Energy Performance of Buildings Directive (EPBD) introduced the concepts of nearly-zero energy building (nZEB) and, more recently, zero-emission building (ZEB). To address the limited research that combines environmental assessment with stakeholder perspectives, this study examines three buildings – a Passive House in Portugal, an nZEB apartment building with enhanced energy efficiency in Czechia, and a ZEB Laboratory in Norway – to explore: (1) which passive and active solutions are implemented, (2) how national and contextual factors shape their adoption and (3) whether the solutions are transferable across different contexts. A mixed-method approach was applied, integrating quantitative life cycle assessment (LCA) with qualitative interviews. Results show that while similar strategies were adopted across all three buildings, their integration was shaped more by economic conditions, regulatory frameworks, construction practices and socio-cultural aspects than by technical feasibility. The LCA highlighted that the load-bearing structures accounted for the largest share of embodied emissions and therefore the greatest reduction potential. The carbon benefits of biogenic materials were found to be highly context-dependent, while the operational advantages of photovoltaic systems outweighed their embodied impacts in all three cases. Overall, the study suggests that accelerating the transition to high-energy-efficiency and low-carbon buildings requires stronger communication between policymakers and practitioners, cross-country knowledge exchange to bridge technical expertise gaps, greater professional guidance and increased market awareness.

Resumo

O setor da construção é responsável por cerca de 33% das emissões globais de gases com efeito de estufa. Para apoiar os objetivos de descarbonização europeus, a *Energy Performance of Buildings Directive* (EPBD) introduziu os edifícios *nearly-zero energy building* (nZEB) e, mais recentemente, os edifícios *zero-emission building* (ZEB). Perante a escassez de estudos que combinem avaliação ambiental com perspetivas de stakeholders, esta investigação analisa três edifícios – uma Passive House em Portugal, um edifício habitacional nZEB na Chéquia e o ZEB Laboratory na Noruega – com três objetivos principais: (1) identificar as soluções passivas e ativas implementadas; (2) compreender como os fatores nacionais e contextuais influenciam a sua adoção; e (3) avaliar se estas soluções são transferíveis para outros contextos. Foi aplicada uma metodologia mista, integrando avaliação do ciclo de vida (ACV) e entrevistas qualitativas. Os resultados mostram que, apesar de estratégias semelhantes terem sido adotadas, a sua aplicação foi mais condicionada por fatores económicos, regulamentares, práticas construtivas e aspetos socioculturais do que por limitações técnicas. Verificou-se que as estruturas portantes representam a maior parcela das emissões incorporadas, evidenciando elevado potencial de redução. Os benefícios de materiais biogénicos mostraram-se dependentes do contexto, enquanto os sistemas fotovoltaicos apresentaram vantagens operacionais que superam os seus impactes incorporados. Conclui-se que a transição para edifícios de elevada eficiência energética e baixo carbono exige melhor comunicação entre decisores e profissionais, partilha internacional de conhecimento, maior envolvimento do setor e sensibilização do mercado.

Palavras-chave: Avaliação do ciclo de vida (ACV), Edifícios de emissões zero (ZEB), Edifícios de energia quase nula (nZEB), Entrevistas a stakeholders, Passive House, Soluções passivas e ativas.

x

Contents

List of Tables

List of Figures

Glossary

BIPV	building-integrated photovoltaics
CA EPBD	Concerted Action – Energy Performance of Buildings
CDD	cooling degree day
CEN	European Committee for Standardization
CLT	cross-laminated timber
CO_2	carbon dioxide
CO_2eq	carbon dioxide equivalent
DHW	domestic hot water
EEA	European Economic Area
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EPD	Environmental Product Declaration
EPS	expanded polystyrene
EU	European Union
GHG	greenhouse gas
GWP	global warming potential
HDD	heating degree day
IAQ	indoor air quality
IEA	International Energy Agency
IEA-EBC	International Energy Agency – Energy in Buildings and Communities Programme
IPD	integrated project delivery
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
net ZEB	net-zero energy building
netZ-WLC	net-zero whole-life carbon
NZB	net-zero building
NZCB	net-zero carbon building
nZEB	nearly-zero energy building
OECD	Organisation for Economic Co-operation and Development
PCM	phase-change material
PH	Passive House
PHI	Passive House Institute

PV	photovoltaic
RSL	reference service life
RSP	reference study period
SH	space heating
VHR	ventilation heat recovery
WLC	whole-life carbon
XPS	extruded polystyrene
ZEB	zero-emission building

1. Introduction

1.1 Role of the construction sector in global GHG emissions

The building and construction sector has a critical role in achieving Europe's ambition to become the first climate-neutral continent by 2050. Globally, the sector accounted for about one-third of energy-related greenhouse gas (GHG) emissions in 2022, comprising 26 % from building operations and 7 % from embodied emissions (International Energy Agency *et al.*, 2023).

1.2 European Union emission reduction targets

Within the European Union's commitment to reduce GHG emissions by 55 % by 2030 compared to 1990 levels and to increase the share of renewable energy (European Parliament and Council of the European Union, 2021), the Energy Performance of Buildings Directive (EPBD) established that new buildings owned and occupied by the public bodies and all new buildings must be nearly-zero energy buildings (nZEBs)[1] by 2018 and 2020, respectively (European Parliament and Council of the European Union, 2010a), and new buildings owned by public bodies and all new buildings must be zero-emission buildings (ZEBs)[2] from 2028 and 2030, respectively (European Parliament and Council of the European Union, 2024). Norway, which is not a member state of the European Union (EU), is obliged to follow the same directive as it is a signatory of the European Economic Area (EEA) Agreement[3].

The potential to decrease GHG emissions and move closer to the European decarbonisation goal in the building and construction industry is also aimed to be fulfilled by adopting the nearly-zero energy buildings (nZEBs) and later zero-emission buildings (ZEBs).

As the EU regulation for the nZEB is already in force and the deadline for the implementation of the ZEB is approaching in the upcoming years, additional measures will have to be taken by the Member States and the states obliged by the EEA to reach the ZEB standard.

---

[1]The nZEB is a building with "nearly zero or very low amount of energy required" that "should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (European Parliament and Council of the European Union, 2010a).

[2]The ZEB is a building with very low energy demand, zero on-site carbon emissions from fossil fuels and zero or a very low amount of operational GHG emissions (European Parliament and Council of the European Union, 2024).

[3]"The EEA agreement brings together the 27 EU member states and the three EEA EFTA states Norway, Iceland and Liechtenstein in an internal market, governed by the same basic rules. It guarantees the EU Single Market's four freedoms, as well as non-discrimination and equal rules of competition throughout the EEA area." (Norwegian Ministry of Foreign Affairs, 2022).

1.3 Motivation

The concept of ZEB was introduced in the 2024 recast of the EPBD (European Parliament and Council of the European Union, 2024), which obliges Member States to establish maximum thresholds for the total annual primary energy use of ZEBs that are at least 10 % lower than the national thresholds for nZEBs at the time of implementation. However, the assessment reported by Maduta and D'Agostino (2024) indicates that the average primary energy use of new buildings exceeds the recommended maximum nZEB thresholds in almost all climate zones.

The successful decarbonisation of the building stock in Europe can be enhanced through further exploration of nZEB and net ZEB concepts, as well as the components used in different case studies. Through lessons learned, solutions that are validated can be implemented in future projects, leading to the further development of a sustainable building stock. The overview of the national regulations and standards, and of the EU legislation transpositions used in different countries, will provide valuable information leading to a better understanding of what the drivers and the hindrances are to moving forward with the decarbonisation of Europe.

This study aims to further investigate available strategies and technical solutions through the analysis of existing "shining examples" of buildings. By learning from the design, construction and operational stages of these buildings, the research seeks to identify how specific solutions and their adaptation in different contexts influence overall building performance.

1.4 Objectives and deliverables

This study aims to explore three case studies of ambitious high-energy-efficiency or low-carbon buildings ("shining examples" of nZEB and ZEB buildings) and perform their net-zero whole-life carbon (netZ-WLC) assessment using life cycle assessment (LCA) (cradle-to-grave) for quantitative comparison. While the goal is to decrease operational energy, such efforts can increase the building's embodied emissions, therefore, it is important to consider the whole life cycle (Maduta and D'Agostino, 2024).

To complement the quantitative results, qualitative research will be conducted in the form of interviews with stakeholders to examine the conditions, challenges and motivations behind projects with strong sustainability ambitions. The outcomes may inform future efforts and support decision-making across all stages of the building life cycle, helping to identify the differences between various contexts – economic, regulatory, professional and socio-cultural – and enabling stakeholders and designers to exchange knowledge and learn from one another across countries.

1.5   Research questions

This study aims to contribute to the scope of the International Energy Agency – Energy in Buildings and Communities Programme (IEA-EBC) project Annex 89 on *Net-zero Whole Life Carbon Buildings*, which focuses on pathways for achieving carbon neutrality in the building sector through reduction of both embodied and operational emissions (see Section 2.1; IEA EBC (2025a)). To guide the research, three research questions were defined:

- **What technical and construction solutions are adopted in the case studies under their respective national conditions?**

  Three case studies will be analysed. The scope of this study includes the involvement of stakeholders participating in the design and construction processes, as well as the lessons learned throughout their implementation.

- **What impact do national and climatic contexts have on the technical and construction solutions adopted in the case studies?**

  Various contextual factors – such as climatic conditions, practices within the construction sector, regulatory frameworks, cultural background, and other influences – may affect the degree of adaptation across countries. The aim is to understand these contexts and analyse the extent of their effects.

- **What challenges and opportunities influence the transferability of the solutions identified in the case studies to different contexts?**

  Knowledge gained from existing energy-efficient and low-carbon buildings can inform the decision-making processes of various stakeholders and guide their implementation in future projects, resulting in positive impacts achieved with less effort.

1.6   Thesis Outline

The thesis is structured into six main chapters:

- Chapter 1 introduces the role of the construction sector in global GHG emissions, outlines the European Union's emission reduction goals, and presents the motivation, objectives, and research questions that frame this study.

- Chapter 2 provides the theoretical foundation and literature background. It defines key terminology used throughout the dissertation, examines existing strategies and barriers related to energy-efficient and low-carbon buildings, reviews relevant EU and national regulations in Portugal, Norway and Czechia and introduces the concept of life cycle assessment.

- Chapter 3 describes the research design and methodology. It details both the quantitative (LCA) and qualitative (stakeholder interviews) components, describes the case studies and their selection, and the data collection and analysis procedures.

- Chapter 4 presents the findings from the LCAs and qualitative research. The results are structured around the research questions highlighting the technical and contextual factors influencing the solutions and their adoption in the three case studies.

- Chapter 5 summarises and interprets the results, exploring the synthesis between the findings and discussing their broader significance across various contexts and implications for future work.

- Finally, Chapter 6 summarises the main insights of the research and provides the overall conclusion.

2. Background

This dissertation examines three examples of low-carbon or energy-efficient buildings, comparing the solutions used and their impact through the whole life cycle. To provide context for the study and demonstrate the relevance of this research, this chapter is structured as follows:

- First, it introduces the context in which the dissertation is written (Sections 2.1 and 2.2).

- Second, it presents the definition framework for this study (Section 2.3).

- Third, it reviews legislative policies at both the international and national levels and their development from the initial regulations regarding energy performance to the current legislative strategies enhancing further development in the building industry (Section 2.4).

- Fourth, it outlines the methods used to evaluate and certify buildings' performance (Sections 2.5 and 2.6).

- Finally, this chapter provides an overview of Portugal, Norway, and Czechia and relevant technical and environmental data to help understand the differences, similarities, and interconnections between the three countries in the context of this study (Section 2.7).

2.1 Context of Annex 89

This study is conducted within the framework of an ongoing project "IEA EBC[4] - Annex 89 - Ways to Implement net-zero whole-life carbon (netZ-WLC)". Annex 89 focuses on "pathways and actions needed by various stakeholders and decision-makers to implement whole life cycle based net-zero greenhouse gas (GHG) emissions from buildings in policy and practice", which includes both embodied and operational energy GHG emissions in all stages of the building life cycle – also referred to as whole-life carbon (WLC). This approach addresses climate change and its negative impacts, supporting the goals of the Paris Agreement (IEA EBC, 2025a). The Agreement aims to limit global temperature increase to well below 2 °C above pre-industrial levels and to pursue efforts to limit it to 1.5 °C (United Nations, 2025), as well as to achieve carbon neutrality by 2050 (European Parliament and Council of the European Union, 2021). This project aims to contribute to the transition of the building sector towards netZ-WLC outcomes (IEA EBC, 2025a). The scope of this study is in a specific part of the project Annex 89, which is Subtask 4 (ST4).

---

[4]"The International Energy Agency – Energy in Buildings and Communities Programme (IEA-EBC) Programme is an international energy research and innovation programme in the buildings and communities field" (IEA EBC, 2025b).

The ST4 aims to develop a better understanding of the conditions (regional needs and contexts) in which the netZ-WLC solutions are implemented. The scope of the ST4 covers the regulation, planning, procurement, and industry initiatives relevant to individual buildings, developments, and entire building stocks. It uses real-world examples of netZ-WLC solutions to analyse the design, assessment processes and initiatives for new construction and renovation. Furthermore, it investigates the stakeholders as well as the regulatory, financial, and organisational structures in various national contexts, examining how netZ-WLC solutions can be applied both within and across countries. These conditions include differing construction practices, regulatory frameworks, financial and organisational systems, cultures, socio-economic needs and climatic factors (IEA EBC, 2025c).

2.2 Literature overview

The literature review for this study was conducted using Scopus database with the advanced search feature and Elicit employing various research questions related to nearly-zero energy buildings (nZEBs), zero-emission buildings (ZEBs), Passive House (PH), the use of life cycle assessment (LCA) as a tool for assessing solutions towards these ambitions, as well as stakeholder experiences with their implementation. To gather information about current practices and research in the field, a wide range of studies was reviewed. This included literature reviews, case studies, and stakeholder review papers, to identify which countries are leading in the research, what the current state of high energy efficiency and low-carbon buildings is, and to understand the practices, challenges, experiences, and opinions in the sector. The purpose was to illustrate why development and implementation of such buildings can be challenging, even with the targets set by EU and the urgency of action being widely recognised.

2.2.1 Previous research

The growing focus on high energy-efficiency buildings can be attributed to the inclusion of nZEBs in the EU regulation, but also to the urgent need for transformation in the building sector to meet climate goals. According to Lou and Hsieh (2024), the number of studies on the topic of nZEB and net-zero carbon building (NZCB) has been rising since 2013. The geographical analysis revealed that the contribution comes from 28 countries, with Italy (13 papers) and Norway (12 papers) in the lead. This contribution is significant in comparison with the rest of contributing countries, with Portugal ranked sixth to eighth (sharing the position with two other countries) with three published papers, and Czechia ranked 17th to 28th (sharing the rank with ten other countries) with one published paper. However, the limited number of case studies achieving the net-zero carbon ambition in literature shows that it is not easy to achieve that ambition (Tirelli and Besana, 2023), although the technical solutions to achieve it are known (Besana and Tirelli, 2022), and are available on the market, including efficient envelopes, energy-efficient appliances, heat pumps, and material-efficient building design (Ohene *et al.*, 2022).

2.2.2 Strategies to achieve high energy efficiency levels in buildings

The strategies to design high-energy-efficiency buildings include passive and active solutions. Passive strategies relate to the location, layout, massing and form of the building and materials, while active strategies typically involve technical systems (Fufa *et al.*, 2016). To achieve an nZEB, the annual energy need has to be covered by renewable energy to a significant extent (European Parliament and Council of the European Union, 2010a). Many studies emphasise that while renewable energy use is essential to meet net-zero (energy or carbon) goals, it is equally critical to reduce the energy needs to minimise capital costs (Ahmed *et al.*, 2022). Construction and technical building features should be prioritised to maximise energy performance, with renewable energy building features implemented as a second step. However, in practice, the first step is often shortcut, and, to achieve a net-zero level, renewable energy capacity is expanded, which greatly increases the need for seasonal energy storage and compromises the benefits of energy-efficient building strategies (Ürge Vorsatz *et al.*, 2020).

The design solutions of nZEBs, such as renewable solar energy (Oliveira Panao and Gonçalves, 2011), may be climate-sensitive, therefore, the design strategies for the different climates should be carefully considered (Lu *et al.*, 2015).

2.2.3 Barriers to nearly zero- and net-zero buildings

In the literature review by Ohene *et al.* (2022), the barriers to the implementation of net-zero carbon buildings (NZCBs) – a concept a step beyond nZEB – are classified into seven categories: economic, legislative, technological, professional/technical, market, social-cultural and geographic. The most discussed categories among the reviewed papers were economic and legislative barriers, whereas the geographical barrier was the least concern. However, Ürge Vorsatz *et al.* (2020) states that it is possible to achieve net-zero or nearly-zero energy building outcomes in the cost range of conventional buildings in most building types and climates, with systems, technology, and skills that already exist. The study was limited to a few expert opinions. Therefore, the authors suggest that the barriers identified should be subject to the broader range of expert views across specific jurisdictions and the results compared with the experts' opinions provided in their study (Ohene *et al.*, 2022). According to Falana *et al.* (2024), identifying key stakeholders throughout the net-zero carbon building life cycle is essential, as a lack of understanding of each role can compromise the success of achieving it. Achieving whole-life net-zero carbon outcomes depends on collaboration among stakeholders. Additionally, this study highlights construction professionals, property/facility users, and policymakers as the most frequently cited key stakeholders. Although a systematic review was conducted, the authors suggest that empirical studies should be conducted on stakeholder analysis in net-zero carbon buildings.

2.2.4 Studies combining quantitative and qualitative approaches

There is limited research combining stakeholder input with the evaluation of solutions' efficiency.

Many existing studies investigate the gap between energy performance predicted at the design stage and real performance observed during the operational stage, incorporating users' experience in terms of behaviour, preferences and comfort (Pannier *et al.*, 2021; Moum *et al.*, 2017; Morris *et al.*, 2016; Menconi *et al.*, 2018). Several studies also evaluate the LCA process itself by the various stakeholders (Alejandrino *et al.*, 2021; Pannier *et al.*, 2021; Sonetti and Lombardi, 2020). Although there are studies that link stakeholder inputs with environmental assessments, the evidence base remains limited. Most of these studies involve only a specific group of stakeholders, which restricts the scope of the findings. Therefore, to build a more complete picture and support decision-making more efficiently, further research is needed.

2.2.5 Implications identified by the literature review

In conclusion, the literature review revealed a limited number of studies that examine specific solutions for achieving net-zero (high-energy-efficiency and low-carbon) performance in buildings – particularly their implementation and environmental impact in real-world projects and their applicability combined with insights from various stakeholders. Net-zero buildings need to be better understood, and their environmental benefits should be evaluated as a part of sustainability assessment (Lützkendorf *et al.*, 2014). This study aims to contribute to this gap by identifying both successful and less effective solutions in terms of environmental performance, as well as practical challenges associated with their implementation, based on the case studies and stakeholder perspectives.

2.3 Definition framework

To ensure clarity in this study, it is crucial to establish a clear definition framework. In the topic of high-energy-efficiency and low-carbon buildings, significant variations in terminology exist, which can lead to inconsistent results across studies and cause confusion that may hinder progress in the field.

2.3.1 Net zero whole-life carbon

The term netZ-WLC, referring to the net-zero whole-life carbon of buildings, expands the "net-zero" concept by considering emissions throughout the whole life cycle of a building, expressed in terms of carbon dioxide equivalent (CO_2eq).

2.3.1.1 Net-zero emissions/carbon and net-zero energy buildings

The "net-zero" generally refers to a way of balancing resource draw from the natural environment and its consumption at a local site (building, block or community), over a specified time period (Lützkendorf *et al.*, 2014). According to Panagiotidou and Fuller (2013) and Wells *et al.* (2018), the term ZEB can be used either for a zero-energy building or a zero-emissions building.

A net-zero emission building offsets all emissions associated with both operational energy and embodied emissions from materials through on-site renewable energy generation (Good *et al.*, 2014). In contrast, a net-zero energy building is energy neutral, delivering as much energy to the grid as it consumes (Panagiotidou and Fuller, 2013) over a period of time, typically a year (Sartori *et al.*, 2012). The term "net" usually implies that the building is connected to the energy grid (Good *et al.*, 2014).

However, various terms continue to appear in literature, as no agreement on clear and universal terminology is between authors (Ürge Vorsatz *et al.*, 2020) for these concepts, resulting in variations in acronyms (e.g., nZEB vs NZEB) and interpretations. While some studies that assess the emissions through CO_2 refer to net-zero carbon building as NZCB or nZCB (Lou and Hsieh, 2024; Tirelli and Besana, 2023; Besana and Tirelli, 2022; Ohene *et al.*, 2022; Bhavsar *et al.*, 2020), some other studies evaluate the emissions through the energy used in buildings referred to as nearly-zero energy building (nZEB). "Net-zero" definitions vary in energy source and supply requirements, timescale, emission source, and grid connection (Moghaddasi *et al.*, 2021).

2.3.1.2 Whole-life carbon assessment

The whole-life carbon (WLC) assessment is based on the LCA methodology originally standardised in ISO 14040 and ISO 14044 (International Organization for Standardization, 2006a,b), which provide the general framework for assessing environmental impacts across a building's life-cycle (see Section 2.5). It consists of 17 modules. Among these, only two modules (B6 and B7) account for operational emissions, while the remaining 15 account for embodied emissions (Tirelli and Besana, 2023).

Incorporating whole life cycle impacts, including the embodied impacts, in the net-zero buildings design process, is important because focusing only on the energy or the energy-associated emissions during the operation stage excludes the impacts associated with the whole life cycle.

The result of whether the building is net-zero (energy or emissions) or not is influenced by several factors, such as the scope and accuracy of the modelling of the building and its life cycle (e.g. service life), as well as the data for energy and GHG emissions. These data need to be known for the results to be interpreted or compared correctly (Lützkendorf *et al.*, 2014). For instance, it may be possible for a design solution with net-zero building ambition to focus only on the operational stage with a heavy environmental impact due to the embodied emissions from the materials and technology systems implemented to achieve the net-zero level (Lützkendorf *et al.*, 2014).

2.3.2 Nearly-zero energy buildings

The nearly-zero energy building (nZEB) is defined in EU regulation as a building with "the nearly zero or very low amount of energy required" that "should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (European Parliament and Council of the European Union, 2010a).

The term nZEB is used as a common practice to assess building performance through energy consumption and to determine the national ambition level for buildings.

2.4 Legislative evolution toward nearly-zero energy buildings: the role of top-down structure

Policies and regulations play a crucial role in increasing demand for net-zero carbon buildings, as they can motivate and guide public stakeholder behaviours and practices towards "zero-carbon" (Pan and Pan, 2021) and an adoption of European Committee for Standardization (CEN) standards allows for better cross-country comparison (Economidou *et al.*, 2020). The cross-country comparison has progressed in a positive direction. However, the national reports collected by Concerted Action – Energy Performance of Buildings (CA EPBD) in 2020 (Fragoso and Baptista, 2021; Brekke *et al.*, 2021; Svoboda, 2021) reveal that the same questions or categories are interpreted differently across countries. As a result, the information provided varies, making it necessary to examine the reports and national regulations more closely for accurate cross-country comparisons.

2.4.1 European Union

1970 – First building sustainability regulation

The development of the legislation promoting the energy efficiency of buildings dates back to the 1970s. The necessity for the buildings' energy behaviour improvement emerged with the oil crisis in Organisation for Economic Co-operation and Development (OECD) countries that led to the price shock (Papadopoulos, 2007). Energy efficiency emerged as an important factor, leading to policy responses that enhanced oil security. The first Energy Efficiency policy adopted, promoted energy savings (affecting also the construction sector) and set the goal of reducing the rate of energy consumption growth (Economidou *et al.*, 2020). The buildings' energy was considered mostly on the thermal aspect, and the regulatory policies focused on the thermal transmittance of the buildings' envelope (minimum thermal insulation thickness) (Papadopoulos, 2007).

1990 – Shifting from solely energy savings to the environmental aspect

In the 1990s, the mindset was shifting and actions at both national and international levels in most

countries were rather environmental than solely for energy savings (Papadopoulos, 2007).

The European Council agreed to stabilise the CO_2 emissions in 2000 at the 1990 level. As the performance levels of the buildings and standards in each Member State varied significantly, the policy action at the EU level was decided. Directives[5] called for all Member States to draw up and implement programs introducing sufficient thermal insulation provisions in new buildings. However, the language used in the Directive did not oblige the Member states to "adopt efficiency requirements or fix a minimum level for the thermal insulation of buildings" (Economidou *et al.*, 2020).

2002 – First Energy Performance of Buildings Directive

The need for an amendment of the current Directive was emphasised and resulted in the development of the Energy Performance of Buildings Directive (EPBD), which was the first cohesive European legal act on energy policy in buildings (R.S. Axelrod, 1992). In 2002, the European Parliament and the Council adopted a Directive on the energy performance of buildings (2002/91/EC) (European Parliament and Council of the European Union, 2002). It aimed to level the variations between the Member States. The Directive also introduced a common framework for the methodology calculation of the integrated energy performance of buildings. All new buildings in EU and countries bound by the EEA agreement have, since 2002, been required to have an Energy Performance Certificate (EPC) that evaluates the energy efficiency of the buildings.

The Directive on the energy performance of buildings (Directive 2002/91/EC (European Parliament and Council of the European Union, 2002)) partially replaced the SAVE Directive. The remaining articles were replaced by the Directive on energy end-use efficiency and energy services in 2006 (Economidou *et al.*, 2020).

2010 – Energy Performance of Buildings Directive amendment and definition of nearly-zero energy building

The EPBD was amended in 2010 (European Parliament and Council of the European Union, 2010b) so that all the Member States adopt the minimum energy performance requirements with the "similar ambition levels in terms of energy savings and greenhouse gas emissions reduction". In this amendment, the concept of nearly-zero energy building has been introduced, obliging Member States to build all new public and private buildings according to the nZEB standard since 2018 and 2020, respectively.

The nZEB concept implementation strategy is not embodied in the EPBD and is left for the Member States to detail their nZEB definitions, as it is dependent on the "building types and climates" (Maduta and D'Agostino, 2024).

2016 – Primary energy thresholds recommendations

---

[5]The early EU energy efficiency policies for buildings constituted the "Construction Products Directive" in 1989, the "Boiler Directive" in 1992 and the "SAVE Directive" in 1993 (R.S. Axelrod, 1992)

To further enhance the implementation of the EPBD, the European Commission published the benchmark thresholds recommendations for the annual primary energy based on the four different climatic zones in 2016 (European Commission, 2016).

Czechia has established the annual primary energy thresholds that are less demanding than the recommended levels for both office and residential buildings (BPIE - Buildings Performance Institute Europe, 2021). In Norway, the requirements are defined in terms of net energy demand per year, which is also less demanding than the recommended values for both commercial and residential buildings (Brekke *et al.*, 2021; European Commission, 2016). Portugal, in contrast, does not use energy thresholds, instead it sets minimum performance standards such as U-values in comparison with the reference building, and the renewable energy contribution is set to a minimum of 50 % for the residential and no limit for the non-residential buildings (BPIE - Buildings Performance Institute Europe, 2021).

2024 – Energy Performance of Buildings Directive amendment and definition of zero-emission building

Before the 2024 recast, EPBD was amended again in 2018 (European Parliament and Council of the European Union, 2018) to align with updated goals for 2030, aiming to promote the cost-effective renovations to decarbonise building stock by 2050 (Economidou *et al.*, 2020). The recast of 2024 (European Parliament and Council of the European Union, 2024) introduced the definition of ZEB[6] and requires Member States to adopt the ZEB standard for new public buildings and private buildings by 2028 and 2030, respectively.

2.4.2 Portugal

Portugal has been in the EU since 1986 (Europa, 2025), therefore, the EU regulations that have been in place since then are expected to be transposed into the national regulations.

1990 – Implementing EU legislation

For many decades, Portugal has lacked in terms of energy performance regulations. In 1990, the first energy efficiency regulation was introduced, but with limited impact on buildings' performance. At that time, preventing building pathologies such as mould growth was one of the most important aspects. However, requirements related to insulation and double glazing have also been introduced (Fragoso and Baptista, 2021).

2006 – Renewable energy thresholds

In 2006, the first regulation for the renewable energy contribution was introduced (Fragoso and Baptista, 2021), and, since then, the limit has remained unchanged.

---

[6]A zero-emission building is one with very low energy demand, zero on-site carbon emissions from fossil fuels, and zero or very low operational greenhouse gas emissions.

Current situation

In the current national regulation, the building requirements are calculated according to the reference building and include maximum heating and cooling needs (average calculated primary energy needs according to the different winter climatic zones) and maximum non-renewable primary energy (Fragoso and Baptista, 2021). For comparison, selected requirements to reach nZEB are presented in Table 1.

2.4.3 Norway

Norway, as it is not a Member State of EU, is not directly bound by the EU directives, but is committed to implementing the directives into its national regulation by the EEA agreement (see Section 1.2). Consequently, the national regulation is adapted with a time span after the EU regulation is set in place.

1997 – Building envelope regulation

The Norwegian regulation on building energy efficiency, as established in 1997, included only indicators on the building envelope (U-values, maximum allowable glass area, airtightness limits) and a minimum efficiency requirement for heat recovery in ventilation systems (Brekke *et al.*, 2021).

Implementation of Energy Performance of Buildings Directive in the national regulation

The Norwegian regulation adopted the EPBD from 2002 (Directive 2002/91/EC) in 2007 (reaching their full effect in 2010), with the energy performance requirements revision in 2015.

The Directive 2010/31/EU was implemented in Norway in 2023. To comply with this Directive, all new buildings are mandated to achieve nZEB. Later amendments are not included in the EEA agreement, but most of the amendments (until EPBD 2018) have been implemented into the Norwegian national legislation (Concerted Action EPBD, 2025).

2015 – Implementation of Passive House standard

The updated code implemented in 2015 mandates all new buildings to follow the Passive House standard (Nykamp, 2020) from 2017 (NS 3700 for residential buildings and NS 3701 for non-residential buildings).

Current situation

In the current code (TEK17), the requirements for the residential nZEBs can be fulfilled by one of two ways: first is achieving the net energy performance (specific energy limits for different building types - kWh/m^2 per year net energy need) (Brekke *et al.*, 2021) and the second is through the specific measures for heat loss, insulation thickness, and other technical specifications (Nykamp, 2020). In non-residential nZEBs, the requirement can only be met through the net energy performance criterion. For comparison, selected requirements are presented in Table 1.

2.4.4 Czechia

The Czech Republic is a member of EU since 2004 (Europa, 2025), therefore, the EU regulations that have been in place since then are expected to be transposed into the national regulations, as well as in Portugal.

1949 – Building heat losses calculation standard

In 1949, the standard focusing on the calculation of building heat losses in central heating design was established (Kubečková and Vrbová, 2021).

1954 – Thermal transmittance

The first national regulation concerning energy efficiency with a specific performance indicator was introduced in the 1954 standard (ČSN 73 0540), later becoming binding[7]. The thermal transmittance limit was evaluated based on the belief that the masonry wall should be 450 millimetres thick, thus the thermal transmission limit corresponded to the thermal performance of a brick wall of that thickness (Pompl, 2017; Kubečková and Vrbová, 2021).

1979-2006 – Stricter thermal transmittance standards

In subsequent Czech technical Standards, the limits for thermal transmittance (later referred to as U-values) became progressively stricter. However, no impact of EPBD on the strengthening of thermal performance requirements was observed (Pejter and Gebauer, 2011).

Current situation

In the current national regulation, the calculation of a building's energy performance is based on a comparison with the reference building. This reference nZEB defines required thermal transmittance (U-values) of the building envelope as well as the primary energy consumption. For a new building to comply with the nZEBs standard, its average U-value must not exceed 70% of the corresponding average U-value of the reference building (Ministerstvo průmyslu a obchodu, 2024). For comparison, selected requirements are presented in Table 1. The obligation to comply with the building's energy performance requirements came into force in 2006 (406/2006 Sb.) and is proven through the EPC (Hudcová, 2009).

---

[7]Any solution with a deviation from the recommended value was mandatory to report to the Ministry of Construction.

Table 1: Comparison of nZEB requirements and thresholds.

Country	Primary energy (PT, CZ) Net energy (NO) [kWh/m^2·yr]	U-values [W/(m^2·K)]			
		wall	**roof**	**floor**	**window/door**
Portugal (Ílhavo)	97 (residential) 256 (non-residential)	0.40 0.60	0.35 0.45	0.35 0.45	2.40/ - 3.30/ -
Czechia	30-70 (heating) 100-160 (total)	0.30 (req.) 0.20 (rec.)	0.24-0.30[**] 0.16-0.20	0.60 0.40	1.50 / 3.5 (req.) 1.20 / 2.3 (rec.)
Norway	100+1600/m^2[*] (small house) 95 (apartment) 115 (office)	0.18	0.13	0.10	0.80 / 0.80

[*] 1600 divided by heated gross internal area
[**] based on the roof type

Note: In Portugal and Czechia, compliance is based on comparison with a reference building. The primary energy thresholds shown in the table are indicative values and are not defined in the building codes as fixed absolute limits. In Norway, non-residential buildings must meet the net-energy thresholds for nZEBs. For residential buildings, compliance may be alternatively met through U-value requirements together with additional measures, such as limits on window and door areas, efficiency of heat-recovery systems and other performance criteria.

Sources:
Portugal: (Fragoso and Baptista, 2021; Ambiente e Ação Climática e Infraestruturas e Habitação, 2021)
Czechia: (Čejka and Antonín, 2017; Svoboda, 2021)
Norway: (Direktoratet for byggkvalitet, 2017)

2.5 Life cycle assessment – method for the whole life carbon evaluation

The LCA is the methodology for integrated assessment of the "environmental burden of products at all stages in their life cycle – from the extraction of resources, through the production of materials, product parts and the product itself, and the use of the product until the management after it is discarded, either by reuse, recycling, or final disposal", which is referred to as "cradle-to-grave" (Guinee, 2002).

In this assessment, the impacts associated with the whole life cycle of products (in the case of this study, buildings) are quantified. The impacts can refer to a wide range of categories, so-called impact categories, such as climate change, resource depletion, ecotoxicity, etc. The environmental impacts refer to the consequences of human interventions in the environment - whether physical, chemical, or biological - such as resource extraction, emissions (including noise and heat), and land use (Guinee, 2002).

The general objective of building LCA is multi-dimensional, aiming to reduce environmental impacts, carbon emissions, energy use, and associated costs (Nwodo and Anumba, 2019).

2.5.1 Life cycle assessment framework

LCA is based on four main phases: goal and scope, life cycle inventory and inventory analysis, impact assessment and interpretation (Cristobal-Garcia *et al.*, 2016).

Goal and Scope

In the goal and scope step, the objectives of the study are defined, including the intended application, the purpose of conducting the study, and the target audience. This step involves the main methodological choices for carrying out the LCA, which include the definition of the functional unit, system boundaries, identification of the allocation procedures, the studied impact categories, the life cycle impact assessment (LCIA) methods used and the identification of data quality requirements (Cristobal-Garcia *et al.*, 2016). The methodological choices will be described in Chapter 3.

Life cycle inventory

Life cycle inventory (LCI) involves the data collection and the calculation procedure for quantification of inputs and outputs of the studied system. System inputs and outputs are, for instance, energy, raw material, and other physical inputs, products and co-products, and waste, emissions to air, water or soil, or other environmental aspects. During the data collection, new requirements, limitations or key findings about acquired data may be discovered, which would result in the necessity to change the data collection procedure so the goals of the study are met, therefore LCI is an iterative process (Cristobal-Garcia *et al.*, 2016).

As a part of the inventory analysis step, the collected data are validated and related to the functional unit defined in a "Goal and Scope" step (Cristobal-Garcia *et al.*, 2016). In whole-life carbon assessments, the functional unit is typically expressed as one square meter of building floor area over the reference study period.

Life cycle impact assessment

Results of LCI are associated with the environmental categories and indicators. Life cycle impact assessment (LCIA) methods classify the emissions into impact categories (Cristobal-Garcia *et al.*, 2016), such as climate change, human toxicity, land use and resource depletion (Sala *et al.*, 2012) in a first step and characterize them to common units to allow the comparison (e.g. all emissions expressed in CO_2eq by using their global warming potential[8]) in a second step (Cristobal-Garcia *et al.*, 2016).

Interpretation

Results from LCI and LCIA are interpreted according to the scope and goal. This step includes completeness, sensitivity, and consistency checks, as well as uncertainty and accuracy of obtained results (Sala *et al.*, 2016).

---

[8]Global warming potential (GWP) is an index to measure how much infrared thermal radiation a greenhouse gas would absorb over a given time frame after it has been emitted to the atmosphere. It is expressed as a multiple of the radiation that would be absorbed by the same mass of added CO_2, which is taken as a reference gas. Therefore, the GWP of CO_2 is 1. For other gases, it depends on how strongly the gas absorbs infrared thermal radiation, how quickly the gas leaves the atmosphere, and the time frame being considered (IEA, no date).

2.5.2 Assessment of environmental performance of buildings

The method for the assessment of the environmental performance of the buildings based on LCA is specified in EN 15978:2011. The approach covers all the stages of the building life cycle, includes all building-related construction products, processes, and services used over the life cycle of the building (CEN, 2012) and is divided into modules for different stages, shown in Figure 1. The goal of the assessment is to quantify the environmental performance of the object of assessment by means of compiling environmental information (CEN, 2012).
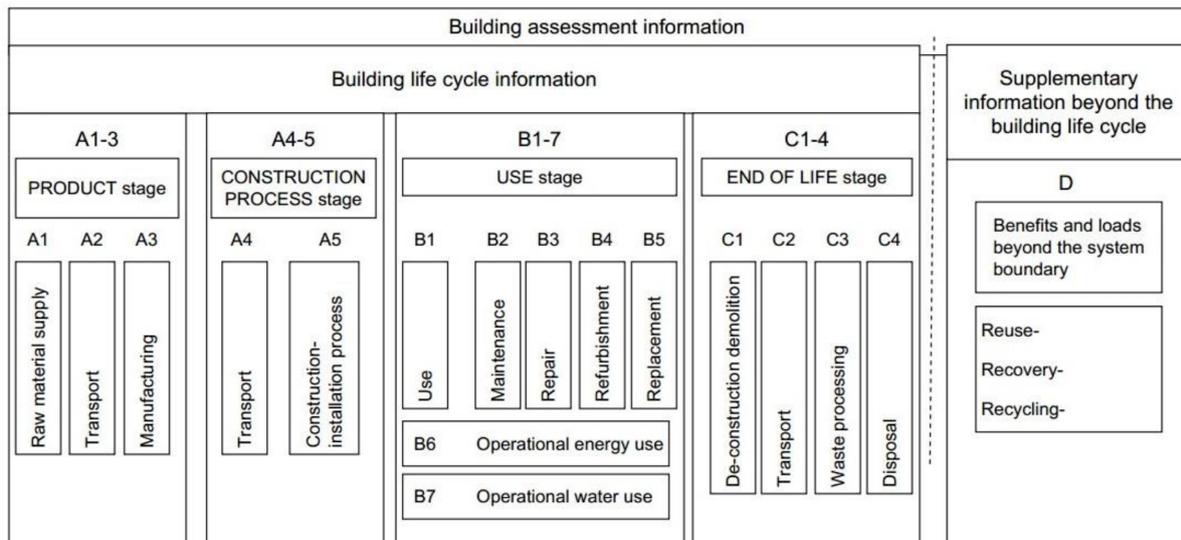
Figure 1: Buildings' LCA stages according to EN 15978 (*Potrč Obrecht et al., 2019*).

2.6 Certifications and building performance ambitions

All new buildings in EU, as well as in countries bound by the EEA agreement, are required to issue an EPC that evaluates energy efficiency of the buildings. Some countries, however, go beyond the mandatory certifications by adopting additional national or internationally recognized schemes.

2.6.1 Passive House standard

Passive House (PH), a building standard founded in Germany by the Passive House Institute (PHI) in 1996, was developed with the vision of promoting buildings that combine high energy efficiency, comfort and affordability. The aim is to reduce heating losses to the absolute minimum. The Passive House concept eliminates the need for traditional heating (or cooling), instead, the indoor air quality (IAQ) and comfort are ensured by the post-air heating systems (Passive House Institute, no date).

For the building to achieve the PH standard, several criteria related to energy demands, airtightness and thermal comfort, must be met. These criteria are summarised in Table 2.

Requirement	Threshold
Space Heating Energy Demand	< 15 kWh/m^2 of net living space (treated floor area) or < 10 W/m^2 peak demand
Space Cooling Energy Demand	< 15 kWh/m^2 of net living space (treated floor area) or < 10 W/m^2 peak demand + allowance for dehumidification
Renewable Primary Energy Demand	< 60 kWh/m^2 of treated floor area per year (Total energy use for all domestic applications – heating, hot water, and domestic electricity)
Airtightness	< 0.6 air changes per hour at 50 Pa (ACH50)
Thermal Comfort	< 10 % of hours over 25 °C in a year

All the criteria are "achieved through the intelligent design and implementation of the five Passive House principles" including the thermal insulation, Passive House windows, ventilation, heat recovery, airtightness of the building and absence of thermal bridges (Passive House Institute, no date). All of the criteria primarily focus on achieving appropriate insulation and ventilation. Nevertheless, the Passive House concept ultimately aims to create energy-efficient buildings (Zavadskas *et al.*, 2017). The criteria are represented in Figure 2 and Table 3.
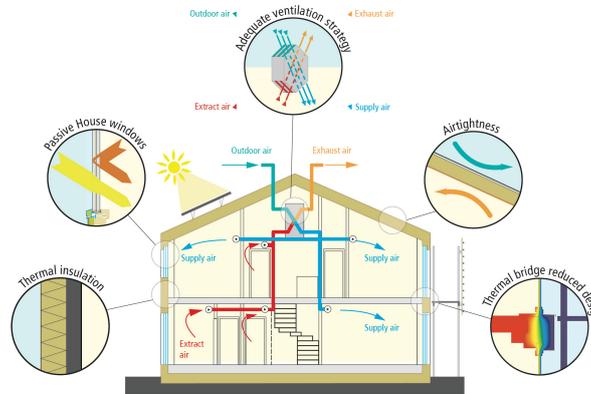
Figure 2: Five Passive House principles (**Passive House Institute**, no date).

While the net-zero energy standard focuses solely on energy consumption, the PH standard is defined based on the consideration of the indoor environment and quality and thermal comfort. The PH standard aiming to lower energy demand (Zavadskas *et al.*, 2017) – saving more than 50 % of the major energy consumption (Feist *et al.*, 2005) – while keeping a good indoor environment, is a key enabler for the net-zero energy building standard (Ahmed *et al.*, 2022).

According to Ürge Vorsatz *et al.* (2020), most literature states that Passive Houses use slightly more materials than conventional houses, however, the reduction in operational energy (heating and cooling energy use) compensates for the potential increase of embodied energy. The reduction of approximately

Principle	Requirement	Notes
Thermal insulation	U-value $<$ 0.15 W/(m²K)	For most cool-temperate climates. Maximum of 0.15 watts lost per degree of temperature difference per square metre of exterior surface.
Passive House windows	U-value $<$ 0.80 W/(m²K) g-values[9] around 50 %	For most cool-temperate climates. Low-e glazings filled with argon or krypton.
Ventilation heat recovery	$>$ 75 % heat recovery efficiency	Heat exchanger transfers more than 75 % of exhaust air heat to fresh air; efficient heat recovery ventilation.
Airtightness of the building	$<$ 0.6 air changes per hour at 50 Pa	Measured during pressurised and depressurised tests; uncontrolled leakage through gaps must be avoided.
Absence of thermal bridges	Thermal bridges avoided or minimised	Thermal bridges that cannot be avoided must be minimised as much as possible.

30 % in total life-cycle energy demand is reached in PH buildings compared to conventional ones (Ürge Vorsatz *et al.*, 2020). Consequently, when houses are built under the PH standard, the price normally rises (Ahmed *et al.*, 2022).

Given that the energy use limit for the PH is less strict than that for nZEBs (Ahmed *et al.*, 2022), the relative share of embodied energy in PH tends to be lower. According to (Chastas *et al.*, 2016), the share of embodied energy in Passive Houses ranges from 11 % to 33 %, and between 74 % and 100 % in the nZEBs, compared to 6 % to 20 % in conventional houses. These differences highlight the importance of conducting the whole life carbon assessment rather than focusing solely on operational energy, as the embodied energy share can vary significantly across building types.

2.6.2 Norwegian ZEB concept

Based on the previous work of International Energy Agency (IEA) and the Energy Performance of Buildings Directive (EPBD) (Kristjansdottir *et al.*, 2014), the Research Centre on Zero Emission Buildings (the ZEB Centre) developed the Norwegian definition of ZEB according to NS-EN15978:2011.

A ZEB is a highly energy-efficient building that compensates for its CO_2-equivalent emissions through on-site energy production (Kristjansdottir *et al.*, 2014), with the balance measured in terms of associated GHG emissions during the building's lifespan rather than direct energy consumption and production

(Fufa *et al.*, 2016).

The ZEB Centre was run by NTNU[10] and SINTEF[11] with the main objective "to develop competitive products and solutions for existing and new buildings that will lead to market penetration of buildings with zero emission of greenhouse gases related to their production, operation and demolition" (SINTEF, 2014). To develop solutions and concepts for zero-emission buildings, it was first necessary to develop the definition of ZEB. The current ZEB-definition was developed based on the ZEB Center research and from seven to eight ZEB pilot building projects (Dokka *et al.*, 2013).

The ZEB definition is established through a range of various ambition levels based on the associated emissions indicated by the first letter of the life-cycle stage[12]. The "Benefits and loads" ("D") are not currently included in the ambition levels, however, information on possible benefits of recycling, reuse and energy recovery is relevant for the choice of appropriate materials during the product stage, and the information should be calculated and included in the emissions analysis report (Kristjansdottir *et al.*, 2014). The final goal of the ZEB Centre are zero GHG emissions related to the production, operation and demolition of the buildings, which is indicated by ZEB-COM[13]. This, according to Dokka *et al.* (2013), is a very ambitious goal that seems to be hard to achieve in real buildings with current available technology.

Six levels of ambition are defined and are represented in Figure 3. The lowest level (ZEB-O÷EQ) requires compensation for operational emissions, excluding the energy use for appliances and equipment. The highest ambition level (ZEB-COMPLETE) requires compensation for the entire life-cycle emissions covering the product stage (A1-A3), construction process stage (A4-A5), use stage (B1-B7), and end of life stage (C1-C4) (Fufa *et al.*, 2016).

The ZEB concept involves two design strategies that align with those used in nZEBs. First strategy is to minimise the need for energy use in buildings through energy efficiency measures, and the second strategy is to adopt renewable energy and other technologies to meet the remaining energy needs (Fufa *et al.*, 2016).

Indoor environment of all ZEB buildings should be at least on the level of any other building (Fufa *et al.*, 2016) and comply with the Norwegian building code (Dokka *et al.*, 2013).

---

[10]Norwegian University of Science and Technology.

[11]SINTEF is a research institute, with multidisciplinary expertise within technology, natural sciences and social sciences. It is an independent foundation which, since 1950, has created innovation through development and research assignments for business and the public sector at home and abroad.

[12]O - emissions associated with Operational energy use; M - embodied emissions associated with building construction Materials; EQ - operational emissions from technical EQuipment; C - emissions associated with Construction and installation; E - embodied emissions associated with the End of life phase of the building (Fufa *et al.*, 2016).

[13]The "C" is related to the construction process of the building, "O" the operation of the building, and "M" the emission related to the material use of the building (including the demolition) (Dokka *et al.*, 2013).

| System Boundary NS-EN 15978:2011 | | | | | | | | | | | | | | | | | D Benefits and loads |
| A1-3 Product Stage | | | A4-5 Construction Process Stage | | B1-7 Use Stage | | | | | | | C1-4 End of Life | | | | |
A1: Raw Material Supply	A2: Transport to Manufacturer	A3: Manufacturing	A4: Transport to building site	A5: Installation into building	B1: Use	B2: Maintenance (incl. transport)	B3: Repair (incl. transport)	B4: Replacement (incl. transport)	B5: Refurbishment (incl. transport)	B6: Operational energy use	B7: Operational water use	C1: Deconstruction / demolition	C2: Transport to end of life	C3: Waste Processing	C4: Disposal	D: Reuse, recovery, recycling
ZEB - O/EQ										*						
ZEB - O										●						
ZEB - OM ●	●	●						**		●						
ZEB - COM ●	●	●	●	●				***		●						
ZEB - COME ●	●	●	●	●				●		●		●	●	●	●	
ZEB - COMPLETE ●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	

* Does not include operational energy of electrical equipment
** Does not include transport to building site (A4), installation into building (A5) or end of life treatment of the replaced materials
*** Does not include end of life treatment of the replaced materials
NB: Biogenic carbon should only be included at a ZEB-COME or ZEB-COMPLETE level

Figure 3: Illustration of ZEB ambition levels according to NS-EN 15978:2011 (Fufa et al., 2016).

2.7   Context of Norway, Portugal and Czechia

For the purpose of this study, three case study buildings located in different countries were selected: Portugal, Norway, and the Czech Republic. The selection of specific case studies was based on institutional collaborations and academic relevance. The climatic and contextual differences between these three countries provide a valuable basis for the comparative analysis within the scope of this dissertation.

2.7.1   Climate and geographical location

Each of the countries is located in a different climate zone with a varying number of the heating degree days (HDDs) and cooling degree days (CDDs), as shown in Table 4. Based on the climate zones, the EU Commission released the recommendation thresholds for the primary energy for different types of buildings.

While in the paper reviewing the barriers to the nZEBs the geographical barrier was ranked as the least concerned in the reviewed literature (Ohene *et al.*, 2022), Ahmed *et al.* (2022) emphasise the importance of the weather on the applicability of various energy-saving strategies. The authors cite higher thermal insulation and airtightness as an example: in heating-dominated buildings results in greater energy savings, while in cooling-dominated buildings, it may hinder the natural cooling effect during longer periods of lower outdoor temperature instead. However, Ohene *et al.* (2022) stresses that the low importance ranking of the geographical barriers may also be caused by the low extent of the

geographical aspect discussed in literature. Geographical location and the climate conditions could limit the extent of NZCBs technologies' adoption, such as solar and wind energy.

Table 4: Climatic and demographic comparison.

	Portugal	Norway	Czechia
Ocean	✓	✓	✗
Climatic zone	Oceanic, Mediterranean	Nordic	Continental
Heating degree days – IEA (2020a,b,c) (°C)	775	3587	2645
Cooling degree days – IEA (2020d,e,f) (°C)	108	5	66

2.7.2 Electricity mixes and energy use for heating

Portugal, Norway, and Czechia exhibit distinct electricity mixes (see Table 5). In Portugal, electricity generation is dominated by hydro (36,4 %), wind (28,2 %), and solar PV (13,9 %)(IEA, 2025a). Norway's electricity supply is predominantly based on hydro (88,9 %), followed by wind (9,2 %)(IEA, 2025b). In contrast, Czechia's electricity generation remains largely dependent on nuclear (40,2 %) and coal (36,3 %) (IEA, 2025c).

Table 5: Electricity mix for Portugal, Norway, and Czechia.

Electricity Generation Source	Portugal (%)	Norway (%)	Czechia (%)
Coal	0,00	0,08	36,3
Oil	2,2	0,0	0,01
Natural Gas	11,0	0,9	5,1
Nuclear	0,0	-	40,2
Hydro	36,4	88,9	4,9
Wind	28,2	9,2	0,97
Solar PV	13,9	0,34	4,9
Biofuels	6,6	-	7,1
Waste	1,2	0,3	0,42
Total	100.0	99.9	99.9

Consideration of the country's electricity mix comes to an importance when conducting LCA. Each country has a different national electricity grid composition, therefore, the same amount of electricity consumption results in different GHG emissions depending on the national energy mix. To account for these variations, emission factors[14] are applied to convert energy use into its associated environmental impacts.

While the context of the electricity mix is important for technological measures such as on-site electricity generation, the actual benefits also depend on the dominant types of heating in each country.

---

[14]Emission factor is "a measure of the expected GHG emissions resulting from the combustion of one unit of a given fuel or from the production of one unit of a given source of electricity (or other secondary energy carrier). It is also used to refer to the weighted average emissions associated with the production of electricity from a range of sources, usually expressed as mass of carbon dioxide equivalent per kWh or per volume of natural gas" (IEA, no date).

In Portugal roughly half of households do not have any source of heating. Among the remaining half, most use mobile heating devices such as electric or gas heaters (the exact share of the energy sources is not specified), while the majority of rest rely on central heating systems or open fireplaces (Insituto Nacional de Estatística, 2022).

In Norway, the dominant energy source for heating across all building types is electricity, with a significant share of the heat being provided through heat pumps (Norwegian Ministry of Energy, 2025).

In Czechia, the largest shares of household heating are still supplied by natural gas and district (central) heating (Český Statistický Úřad, 2021), although the use of electricity and heat pumps is steadily increasing. District heating systems mainly rely on coal and natural gas as fuels (Ministerstvo průmyslu a obchodu, 2022).

2.7.3 Share of renewable energy in final energy consumption

Renewable energy plays a critical role in addressing the challenges of fossil fuel exhaustion and of the climate change (Ahmed *et al.*, 2022).

Norway shows the highest share of modern renewables in final energy consumption (61.36 %), followed by Portugal (32.33 %), whereas Czechia remains the lowest (17.16 %), as presented in Table 6. While Norway's share of renewable energy remains almost the same since 2000 (with 2 % rise), Portugal increased the renewables final energy consumption by 61 % and Czechia by 189 % (IEA, 2025b,a,c).

Table 6: Share of modern renewables in final energy consumption (2021) and trend from 2000-2021 (IEA, 2025b,a,c).

Country	Share of modern renewables (%)	Trend (change 2000-2021) (%)
Portugal	32.33	61
Norway	61.36	2
Czechia	17.16	189

2.7.4 Emissions and the temperature rise

The operational energy of the buildings accounts for 30 % of global final energy consumption and 26 % of global energy-related emissions (direct emissions and indirect emissions from electricity production) (IEA, 2025d). In terms of emissions, Portugal and Norway each contribute to 0.1 % of global emissions, while Czechia contributes 0.27 % (IEA, 2025a,b,c). Temperature rise per year is the lowest in Portugal (0.02 °C), slightly higher in Norway (0.03 °C), and the highest in Czechia (0.06 °C). For an overview, see Table 7.

Table 7: Emissions data for Portugal, Norway, and Czechia in 2022 (*IEA, 2025a,b,c*).

Category	Portugal	Norway	Czechia
Share of Global Emissions (2022) (%)	0.10	0.10	0.27
Share of Global Emissions (2022) (Mt CO_2)	36	36	91
Temperature Rise (°C per year)	0.02	0.03	0.06

Note: Mt CO_2 stands for metric tons of carbon dioxide.

3. Methods

The methodology of this study combines qualitative and quantitative research based on three case studies of high energy efficiency buildings with different contexts and energy efficiency or carbon footprint ambition levels.

Qualitative data were collected by semi-structured interviews with the stakeholders involved with the case studies or more broadly in the area of energy-efficient buildings, such as policymakers, actors involved with certifications or sustainability in buildings.

3.1 Case studies

For the case studies, three buildings were selected: Rua do Mar family house (Ílhavo, Portugal), ZEB Laboratory (Trondheim, Norway), and Dřevák (Prague, Czechia).

The selection followed an information-oriented approach and aimed to capture contextual diversity rather than representativeness. As Flyvbjerg (2006, pp. 229–230) explains, "when the objective is to achieve the greatest possible amount of information on a given problem or phenomenon, a representative case or a random sample may not be the most appropriate strategy … it is more appropriate to select some few cases chosen for their validity". Specifically, this study applies the approach of "selecting maximum variation cases", which enables researchers "to obtain information about the significance of various circumstances for case process and outcome" that differ across dimensions such as size, form of organization, location and budget.

Each building was constructed in a different period and under distinct circumstances, with varying energy efficiency and carbon reduction ambitions. An overview of the key characteristics of the case studies is presented in Table 8.

Table 8: Key characteristics of the case studies.

	Rua do Mar	**ZEB Lab**	**Dřevák**
Location	PT	NO	CZ
City	Ílhavo	Trondheim	Prague
Year of completion	2012	2021	2027
Type	detached family house	office	apartment building
Use type (functionality)	residential	non-residential	residential
Treated floor area (m^2)	223,7	1742	
N° Stories (above/under ground)	3/0	4/0	4/1
Stage	built	built	construction
Certification / ambition	Passive House	ZEB-COM	aspiring for BREEAM Excellent, WELL for Residential

3.1.1 Rua do Mar B – Family house

"Rua do Mar B"[15] (Figure 4) is a family house in Ílhavo, a town located in the centre-north coast of Portugal, a transition between Oceanic and Mediterranean climate zones.

*Figure 4: Portuguese case study - Rua do Mar (**Passive House Buildings**, no date).*

This house is the first Passive House-certified building in Portugal. It is a 4-bedroom, 3-storey house with a floor area of about 224 m^2.

Initially, the house was designed to reach high energy efficiency, but not the Passive House standard. After construction began, the owner discovered the Passive House standard, and it was decided to adapt the house to the concept. Furthermore, the idea was extended beyond the energy performance, defining both food and water sectors by developing the WEFI-Building concept - "Water Energy Food almost Independent building". Additionally, the building was certified by LiderA[16] with A+ rating (factor approx 4× current practice, i.e. 4.00).

---

[15]The family house is a semi-detached house with two units - A and B. In this dissertation, only house B is studied. The labelling "A" and "B" is for reference and does not indicate the order of the construction.

[16]Portuguese voluntary system for sustainability assessment of construction.

The systems used in the house to achieve the Passive House standard and high energy efficiency ambitions are a heat recovery ventilation unit, six photovoltaic panels, two solar thermal panels for domestic hot water, rainwater harvesting for irrigation and toilet flushing (with 10 000 liters tank), and fruit and horticultural production.

Heat supply is secured mainly by air; additionally, two small water radiators are installed to provide heat also to the first level, where heating by air would not be sufficient, connected to the fireplace burning wood with a hot water exchanger. When the temperature drops to 20 ºC, the owner can activate the fireplace burning wood.

Three combined sensors (one on each floor) monitor indoor air temperature, relative humidity, and CO_2 concentration. Monitoring also includes electrical consumption (including the compact unit) and water use.

The structure consists of reinforced concrete with thermal masonry infill, reinforced concrete foundations, and expanded polystyrene (EPS) thermal insulation. The roof is made of reinforced concrete with extruded polystyrene (XPS) thermal insulation and finished with ceramic tiles.

3.1.2 ZEB Laboratory – Office and living lab

ZEB Laboratory (Figure 5) is a living office located in Trondheim, the Nordic climatic zone, at NTNU Gløshaugen campus. It is a four-storey, 1742 m^2, full-scale office building, where building facades, components and technical systems can be modified and replaced, which forms a living laboratory – "a laboratory, where people using it as an ordinary office building or for educational purposes become an experimental parameter giving variations in loads with their use of the premises" (NTNU and SINTEF, no date).

When the project preparation started in 2016, the ZEB concept was very new, and every component of the building was experimentally explored. The ambition of ZEB-COM was set from the beginning by the client, and the process was all adapted around this ambition. First, a ZEB cell was built and some concepts were tested in a small scale (The Research Centre on Zero Emission Buildings, no date) and lessons learned were used to adapt the full-scale office.

The investigation and demonstration of new technologies in a full-scale office building is reducing the risk for the "first movers" starting to implement ZEB levels in their buildings' design and construction. The ZEB Laboratory is adaptable, therefore, different building types and configurations can be investigated (NTNU and SINTEF, no date).

The laboratory is connected to the Gløshausen local energy ring grid with a separate heat energy supply and electricity tariff. The ZEB Laboratory generates electricity using roof and facade-integrated solar panels. It is not equipped with its own electricity storage, but the excess energy is used for the

Figure 5: Norwegian case study - ZEB Lab (m.c.herzog / visualis-images, 2022).

Gløshaugen energy campus' needs. The excess heat is stored in the thermal storage developed at ZEB Laboratory itself, utilising the phase change of bio-wax, with a capacity of 200 kWh. The stormwater management system manages the run-off water collection around the laboratory facilities and directs it to the detention reservoir. The water can then be either controllably released into the drainage system or used as a serviceable resource (e.g. watering the green areas, washing the bicycles). To preserve the architectural expression of the building and maximise the roof area for building-integrated photovoltaicss (BIPVs), the interior gutter system was developed.

For research of different types of ventilation, it adapts a variety of ventilation systems. The building is climatised by natural cross-air ventilation, mechanical devices (balanced ventilation), or by the hybrid system combining the two (SINTEF and NTNU, no date).

Heat supply is provided through radiators with water heated primarily by heat pumps, supplemented in colder periods by the district energy grid.

The laboratory is equipped with 1500 sensors (temperature and humidity), two twin rooms with 11 work-stations each, with control functions to enable data collection.

The superstructure is constructed using timber and cross-laminated timber (CLT) panels, supported by a reinforced concrete foundation slab.

3.1.3 Dřevák – Apartment building

"Dřevák" (Figure 6) is one of three residential buildings in a complex located in Prague, within the continental climate zone. Currently under construction, the building will comprise four storeys and a total of 80 units (studios and one-bedroom apartments), making it the largest residential wooden building in

Czechia to date.

*Figure 6: Czech case study – Dřevák (**Skanska Residential**, no date).*

To achieve the high energy efficiency standard (aiming for BREEAM Excellent and WELL for Residential certifications), the building incorporates heat recovery ventilation units, solar thermal panels for the domestic hot water, floor heating, wastewater heat recovery and greywater re-use for toilet flushing. Photovoltaic (PV) panels will also be installed on the green roof. The underground parking will be equipped with a network for electric vehicle charging.

The superstructure is designed using CLT panels while the substructure, serving as underground parking, is constructed of reinforced concrete. The green roof and the surrounding green areas are designed to mitigate the urban heat island effect.

3.2 Quantitative research – Life Cycle Assessment

LCA is used to assess and analyse the environmental impact of buildings, throughout its whole life-cycle, based on the material and energy input and the emissions released to the environment (Ahmed *et al.*, 2022) and in this study serves as a tool to analyse the measures towards energy efficiency in selected case studies.

As a basis for the quantitative case studies analysis, the LCAs of the Norwegian and Czech case studies were obtained from the clients, who performed the analysis for the ZEB-COM assessment and BREEAM certification, respectively. The Norwegian LCA was performed using an Excel-based tool (the ZEB tool) developed by the SINTEF research centre, the Czech LCA was carried out using the One Click LCA software, and the Portuguese LCA for this study was performed manually using Excel together with available EPDs. The LCA analysis for the Portuguese case study (Rua do Mar family house) was

performed as a part of this study and the summary is included in Appendix C.

For the quantification of the mass flows, the bill of materials was obtained from the engineers of the Rua do Mar family house. Building parts defined as a whole were disaggregated, and the final bill of materials used for the LCA was obtained. The LCA was performed manually in Microsoft Excel, using materials' Environmental Product Declarations (EPDs). For materials without an available EPD, the databases were searched for the closest possible match. The search method followed these steps: (1) specific EPD; (2) EPD from Portugal or the geographically closest country; (3) EPD with the closest compounds/composition; (4) the most recent EPD.

The transportation module (A4) was calculated using EPDs for products manufactured in Portugal; for other products, real distances from Portuguese warehouses to the construction site were applied. Construction activities on site that were not specified in EPDs were excluded as the information was not available.

The LCA system boundaries for all case studies are presented in Figure 7.

3.3 Qualitative research – Interviews with stakeholders

Qualitative research is an approach that allows for examining people's experiences (Hennink *et al.*, 2025). One of the research methods is in-depth interviews, which is widely applied in the built environment (Dadzie *et al.*, 2018) and can be used to gather knowledge from different stakeholders such as construction company owners, professionals involved in building management, and other experts in the field (Bavaresco *et al.*, 2020).

In-depth interviews are used when seeking information on individual experiences about a specific topic (Hennink *et al.*, 2025) – as defined by the scope of the Annex 89 project, this study seeks personal experience and context of decision making.

3.3.1 Stakeholders Review – Participant recruitment

Falana *et al.* (2024) identified the three most cited key stakeholders as the construction professionals, property/facility users, and policymakers.

Potential participants were identified by consulting the publicly available data about the projects and through the contacts provided by the study supervisors.

Participants were sampled to recruit stakeholders representing a range of backgrounds, different project stages, and contrasting points of view. However, the qualitative research does not require a specific sample size (Busetto *et al.*, 2020; Morris *et al.*, 2016).

Figure 7: System boundaries.

The figure depicts the system boundaries based on NS-EN 15978:2011, organized into the following life cycle stages:

A1-A3 Product Stage
- A1: Raw Material Supply
- A2: Transport to Manufacturer
- A3: Manufacturing

A4-A5 Construction Process Stage
- A4: Transport to building site
- A5: Installation into building **

B1-B7 Use Stage
- B1: Use
- B2: Maintenance (incl. transport)
- B3: Repair (incl. transport)
- B4: Replacement (incl. transport) ***
- B5: Refurbishment (incl. transport)
- B6: Operational energy use (*, PV-, GR-NO, GR-CZ)
- B7: Operational water use

C1-C4 End of Life
- C1: Deconstruction / demolition
- C2: Transport to end of life
- C3: Waste Processing
- C4: Disposal

D Benefits and loads beyond the system boundary
- D: Reuse, recovery, recycling (M, EX, PV)

Legend:
- Rua do Mar Family house
- ZEB Laboratory
- Dřevák Residential building

* Does not include operational energy of electrical equipment.

** Installation into building includes only values listed in EPD

*** Does not include end-of-life treatment of the replaced materials.

^ At a ZEB-COM level, waste generated from installation (A5) does not include end-of-life treatment, but emissions from A1 - A5.
ZEB Laboratory: Biogenic carbon should only be included at a ZEB-COME or ZEB-COMPLETE level (not ZEB-COM)
ZEB Laboratory: Module D includes on-site energy production, required by the building during operation, and that which is exported to the grid.

PV-   On-site PV generation substracted from the energy demand.

GR-NO   Eneregy demand emmissions as if was recieved from the grid, PV generation not taken into account.

GR-CZ   Energy demand from the grid – Czech residual electricity mix and natural gas, PV generation not taken into account.

M Benefits listed in EPDs of the materials.

EX Benefits from exported on-site generated energy (surplus to building demand).

PV Benefits of all on-site PV generation.

Note: B6 module represents operational energy demand as indicated for each case: ZEB Laboratory – grid emissions only (on-site PV excluded, excess exported PV benefits included in D), Dřevák – grid emissions only (PV benefits included in D), Rua do Mar – grid demand reduced by on-site PV generation.

In total, 15 semi-structured interviews and two written interviews were completed (see Table 9 for the participant list). While the geographical distribution of participants was not proportional, the sample included a variety of stakeholders from several regions and stages to some extent.

Table 9: List of participants.

Identifier	Role	Employer
NO1	Project team	University
NO2	Innovation team	University
NO5	ZEB user	University
NO6	ZEB user	University
NO7	ZEB user	University
NO8	Design team	Construction and civil engineering company
NO10	Energy, sustainability concept design team	Architecture firm
NO11	PhD student	University
PT3	Project team	Design-build firm, Passive House certifier
PT4	Construction team	Construction company
PT9	Policy maker	Agency for Energy (non-profit org.)
PT14	Passivhaus Institut Certifier	Passivhaus Institut
PT15	Project team, user	Design-build firm, Passive House certifier
PT17	Architectural team	Architectural company
CZ12	Sustainability, project team	Construction and development company
CZ13	LCA advisor	CTU (Czech Technical University) research centre for sustainable buildings
CZ16	Project team	Construction and development company

3.3.2 Semi-structured interviews

The semi-structured interviews are characterised by the open-ended nature, allowing for flexibility and new topics to emerge, which also helps to overcome focus solely on topics already known or expected by the researcher (Busetto *et al.*, 2020). The instrument for conducting the interviews is the interview guide (Hennink *et al.*, 2025; Busetto *et al.*, 2020) that remains largely the same throughout the whole data collection process. Only small changes are made, such as refining a question or writing a note on the interview guide as a reminder for the next interview (Hennink *et al.*, 2025). The interview guide was adjusted only for the participants who represented different positions than the majority, such as policymakers and certification stakeholders.

Qualitative interviews are usually conducted face-to-face or through video conference, as they provide an interactive component of the method (Denzin and Lincoln, 2011). However, two of the participants expressed discomfort providing an interview in spoken English, therefore, the interview guide with the questions was provided to them so they could participate in written form.

3.3.3 Ethics

The ethical standards need to be considered when conducting qualitative research, and either local rules or national rules must be followed (Bavaresco *et al.*, 2020). The guidelines followed were provided by NTNU, as the research was conducted while on an internship at that university. The guidelines require following the procedure based on the classification of the data confidentiality. The personal data collection and processing need to be notified to the Sikt[17], which evaluates the data collection, processing, and storage procedures and provides consent to perform the research.

Potential participants were familiarised with the dissertation topic and the way the data would be collected before giving preliminary consent and establishing the date and time slot for the interview. Before the interview, the participants were sent an Information letter (see Appendix A) describing their rights and the data collection and processing protocol in detail. Consent was given orally at the beginning of the interview.

3.3.4 Data processing – Transcription

The interviews were recorded and transcribed using a transcription program[18] in accordance with NTNU data processing guidelines. The text was manually reviewed several times and transformed into the desired form. In the case of Czech-speaking participants, the interviews were conducted in Czech, as it is the native language of the author as well, which allowed the participants to be more open during the dialogue, as the language was not a barrier. In this case, the translation was obtained using an AI tool[19] and reviewed manually to ensure that the meaning was not lost in translation.

To validate the transcriptions, correct or clarify unclear issues, and uphold research ethics (Mero-Jaffe, 2011), the participants were provided with the transcript for review.

The information letter and the interview guides are attached in Appendix A and Appendix B, respectively.

Transforming the speech into written form is an interpretative process and requires making judgments about the collected data. Different levels of detail and forms of transcription are necessary for projects with a variety of aims (Bailey, 2008), as decisions about transcription can influence research outcomes (Oliver *et al.*, 2005). The transcripts are using the combination of naturalism (which captures all details and expressions) and denaturalism (in which grammar is corrected and interview noise, such as pauses, is removed) (Oliver *et al.*, 2005). Denaturalism is used when the content is more important than the "mechanics of interview" (Fairclough, 1992), which was the case of this study. However, as the analysis is performed solely based on the transcripts, some elements of naturalism are used to ensure that

---

[17]"Norwegian Agency for Shared Services in Education and Research is a public administrative body under the Ministry of Education and Research" (Sikt, no date).

[18]Program Netskjema Dictaphone app is used to record and transcribe data, which are qualified as personal.

[19]Before providing any data to the AI tool, the transcript in the original language was reviewed and any data identified as personal – data that could lead to the identification of the participant – was removed. Any data that included personal information was translated manually.

the conclusion is not made out of the statements that were expressed with uncertainty apparent from non-verbal communication.

3.4 Data analysis

3.4.1 Life cycle assessment (LCA)

Considering that the LCAs of the case studies were performed by different actors and apply various system boundaries, reference study periods (RSPs), and other methodological assumptions, relative whole-building results provide the most consistent basis for comparison. To reduce inconsistencies caused by different RSPs, impacts of specific components and technologies were normalised to $kgCO_2eq/m^2$ rather than $kgCO_2eq/m^2/year$.

3.4.2 Contextual study

The approach used in this study is thematic data analysis, which involves capturing patterns or recurring ideas – themes – throughout the datasets. Instances are not required to appear a specific number of times to be considered relevant. As Braun and Clarke (2006) explains, "A theme captures something important about the data in relation to the research question, and represents some level of patterned response or meaning within the data set."

The analysis begins with the time-consuming yet essential process of familiarisation with the data through the reading and review of interview transcripts. This step facilitates the researcher's general understanding of the collected data (Braun and Clarke, 2006).

In the next step, the data was read repeatedly and coded – labelled with one or more short descriptions (Busetto *et al.*, 2020). Codes were developed inductively through reading the data (Hennink *et al.*, 2025), therefore, without trying to fit in a pre-existing coding frame or researchers' preconceptions (Braun and Clarke, 2006). In this study, coding was performed manually using NVivo software. Once all data have been coded, the codes are reviewed, reorganised, and grouped according to their thematic connection, creating broader categories known as themes (Braun and Clarke, 2006). Finally, the identified themes were connected to the research questions to address the aims of the study.

4. Results

As a basis for this study, three case study buildings were selected to compare different conditions and the way the national contexts impact the solutions used. Moreover, as some of the stakeholders are involved with case studies indirectly (policymaker, Passive House certifier), the interpretation goes beyond the case studies and discusses the context of each country out of the scope of the case study buildings.

4.1 Technical solutions

This section answers the first research question by examining which solutions were implemented in different case studies and which of them stakeholders emphasised as the most important or the most effective. The focus is on passive and active measures influencing embodied and operational emissions.

The question is *"What technical and construction solutions are adopted in the case studies under their respective national conditions?"*.

The solutions and measures to reach the high efficiency standard already exist (Ürge Vorsatz *et al.*, 2020), and the case studies are a proof of concept. Only one of the solutions discussed in this study – bio-wax heat storage – can be considered a front-runner technology. The Portuguese case study targets Passive House, the Czech case study nZEB with an improved energy efficiency, and the Norwegian case study ZEB (ZEB-COM). First, this section will explore passive solutions, and second, active solutions.

To complement the qualitative insights from stakeholders, the analysis incorporates the quantitative perspective of the LCA. By examining the distribution of global warming potential (GWP) across life-cycle stages, it becomes possible to identify where the most significant emissions occur and, consequently, what mitigation measures should be applied.

Figure 8 illustrates how the life-cycle GWP is distributed across stages (A1-A3 to D). Across all cases, production (A1-A3) and operation (B6) dominate total emissions, together representing approximately 75-83 % of total impacts. Both ZEB Laboratory and Dřevák reveal the dominance of operational (B6) emissions.

Both buildings also demonstrate strong contributions in module D (about -36 % and -64 %), reflecting the benefits of renewable energy generation. However, the comparability of these benefits is limited due to differences in LCA scope. In Rua do Mar, the PV-related benefits are included under operation (B6); in Dřevák, they are accounted for in module D; and in the ZEB Laboratory, only exported electricity contributes to module D, while PV electricity consumed on site is excluded from the LCA balance and used solely for ZEB-COM balance validation rather than allocation.
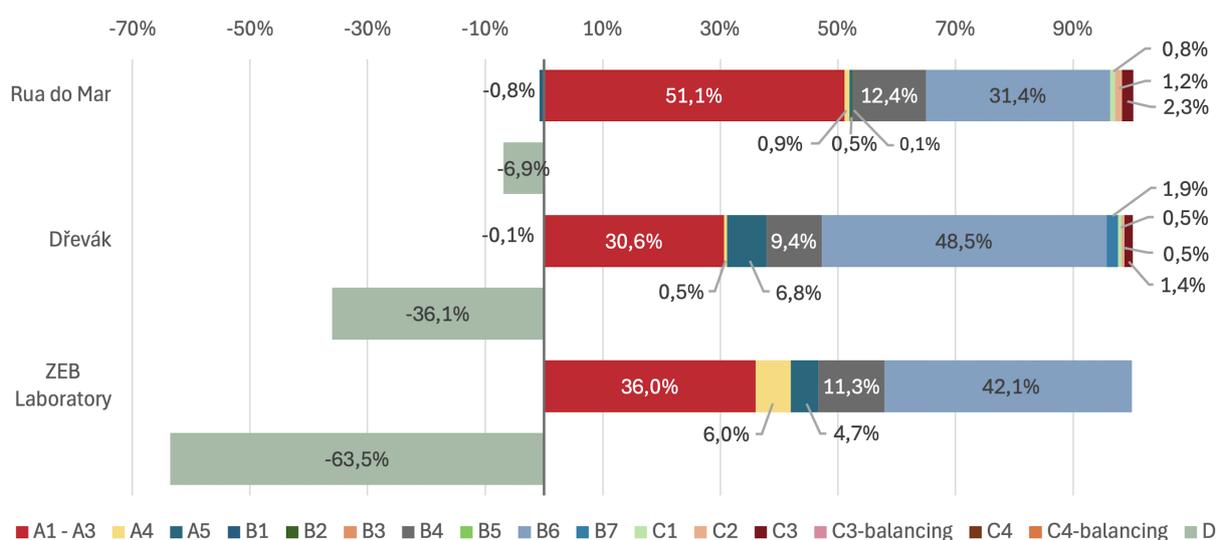
Figure 8: Distribution of life cycle GWP by stage.

The ZEB Laboratory's higher share in the transport stage (A4) may be attributed to its non-traditional building shape and the use of new technologies that may be imported, or Norway's geographical characteristics and location, though this assumption is not empirically verified and would need to be examined further. The absence of the construction stage (A5) in Rua do Mar results from the study scope excluding the construction phase, as the uncertainty and lack of information would have led to speculative results.

4.1.1 Passive solutions

Passive solutions address both the production stage (A1-A3) through materials and design choices and the operational stage (B6) by optimising energy demand. Together, production and operational stages are the largest contributors to carbon emissions in the case studies (see Figure 8). Therefore, early-stage optimisation of the building design and material selection has great potential to reduce embodied carbon emissions.

4.1.1.1 Early-stage optimisation (form, compactness, insulation, glazing)

Among passive solutions, an early-stage design optimisation was emphasised by stakeholders across all case studies (PT3, PT14, PT15, PT17, CZ13, NO1, NO10). Compact building shape was perceived as a way to minimise thermal bridges (PT3, PT4, PT15) and optimise the amount of insulation (PT3, PT4), thereby reducing both carbon emissions (NO8) and cost (NO11). Early-stage optimisation includes conceptual design decisions such as the building form, orientation, compactness, material selection and technical solution choices.

In the Norwegian case study, early-stage optimisation played a role in reaching the ZEB-COM target.

The ZEB Laboratory was designed with a non-traditional diamond shape to increase the roof and facade area and maximise the photovoltaic potential. This optimisation enables electricity production throughout all seasons, meeting all energy needs with on-site generation and even exporting the excess energy (NO8, NO10).

Highly efficient windows were also mentioned as a part of the design optimisation – in Portugal, they were considered equally important as thermal insulation (PT3, PT9, PT15), although not generally prioritised to the same extent.

These measures together define the building envelope and its performance and determine a big part of the building's energy demand before any active system is introduced. Overall, the optimisations and design choices play a decisive role in reducing energy demand and embodied emissions.

4.1.1.2 Material selection (structure and envelope)

In the Czech case study, the primary reasons for choosing a timber structure were to reduce primary energy use and to gain experience with large-scale timber construction. The design aimed to achieve a structural profile as slim as that of a reinforced concrete system while still meeting fire safety and acoustic requirements. The process showed that an alternative calculation method made fire safety compliant without additional fire-proof gypsum board layers that would have increased embodied emissions (CZ16) and partially offset the benefits of timber construction.

In the Czech and Norwegian case studies, structural material choice was linked to primary energy use and emissions reduction goals, respectively. The ZEB Laboratory employs a fully timber superstructure, whereas Dřevák combines a timber superstructure with reinforced concrete elements. Figure 9 illustrates the distribution of embodied emissions among main building elements (foundations, superstructure, inner walls, flooring, roof, finishes, and mortars). Across all three case studies, the superstructure and outer walls consistently account for the largest share of embodied emissions, with 28-39 % and 10-30 %, respectively. This pattern is especially strong in Dřevák and ZEB Laboratory, confirming that the load-bearing system remains a dominant source of emissions, even in buildings with a carbon reduction focus. In all three buildings, the outer walls category includes insulation materials (although not load-bearing materials), increasing this building element's impact. As one stakeholder noted, this outcome is expected, as these elements account for the largest material volumes and share of total embodied emissions:

"And of course, at the moment, . . . the inputs are mainly the emission-intensive materials used in large volumes – typically concrete, steel, bricks, even CLT panels and other influencing factors." (CZ12)

In the Rua do Mar case, a pattern similar to the other two cases is observed. However, all finishes, including those applied to exterior surfaces, are categorised under "paints and finishes". As a result, their contribution is not included within the outer wall category, unlike in the other two cases. This

classification lowers the relative impact of the outer walls in the Portuguese case and influences the timber structure benefits comparison.
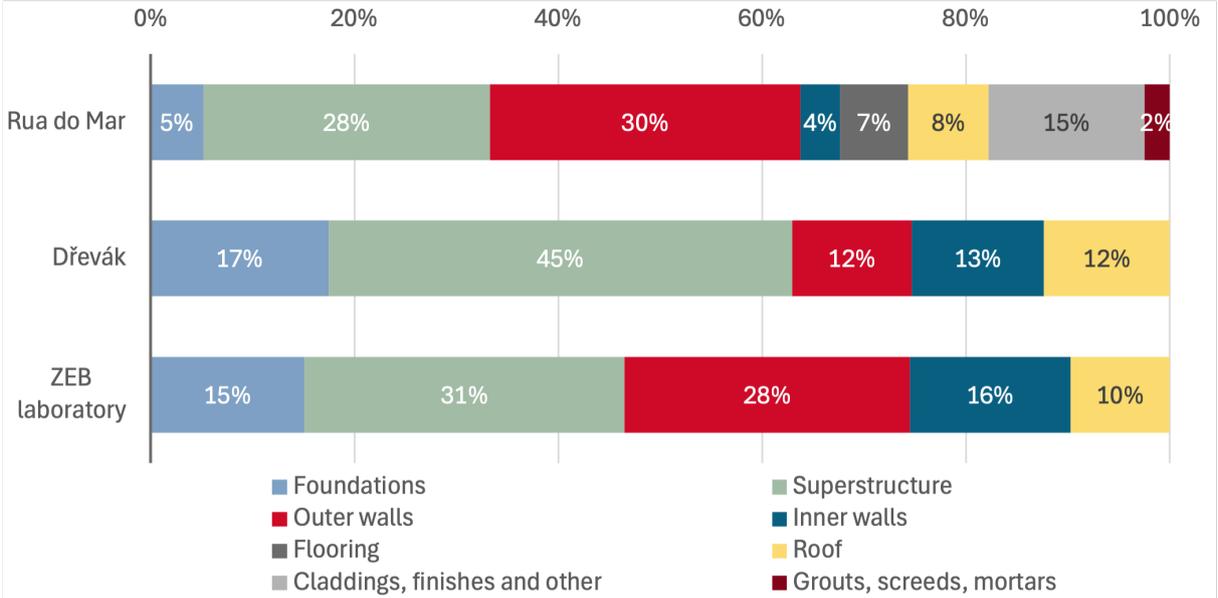
Figure 9: Element-level distribution – A-C stages – non-biogenic carbon.

Note: For comparability, the biogenic impact is omitted as it is not included in the ZEB Laboratory LCA.

The results of distribution of embodied emissions among main building elements suggest that the structural material selection is a major determinant of embodied emissions and adopting timber structures can significantly reduce life-cycle emissions across other contexts, regardless of climate zone.

Thus, material selection and early design integration (form and structure) interact, shaping both embodied and operational performance and offer the highest opportunity for embodied carbon reduction.

4.1.1.3 Structural comparison of embodied emissions – biogenic and fossil impacts

The distinction between structural materials becomes apparent not only in terms of fossil-related emissions but also through their capacity to temporarily store carbon during the building's life cycle. Figure 10 compares the GWP category contributions (fossil, LULUC and biogenic) for the main structural elements – substructure, superstructure and roof. Since the ZEB Laboratory's LCA excludes biogenic reporting, its results are presented as total non-biogenic impacts.

In the superstructure, Dřevák exhibits a substantial negative biogenic component (-141.49 kgCO$_2$eq/m^2), reflecting significant carbon storage within its timber elements. In contrast, Rua do Mar shows only a minor biogenic contribution (-3.79 kgCO$_2$eq/m^2), originating from wooden components such as flooring. The fossil-related emissions are comparable for Rua do Mar and Dřevák (~108 kgCO$_2$eq/m^2) but considerably lower in the ZEB Laboratory (51.1 kgCO$_2$eq/m^2). This difference between the two timber-based buildings (Dřevák and ZEB Laboratory) may be attributed to the use of concrete elements (e.g. slabs and beams) in Dřevák, as well to differences in building typology. The open-space office and residen-
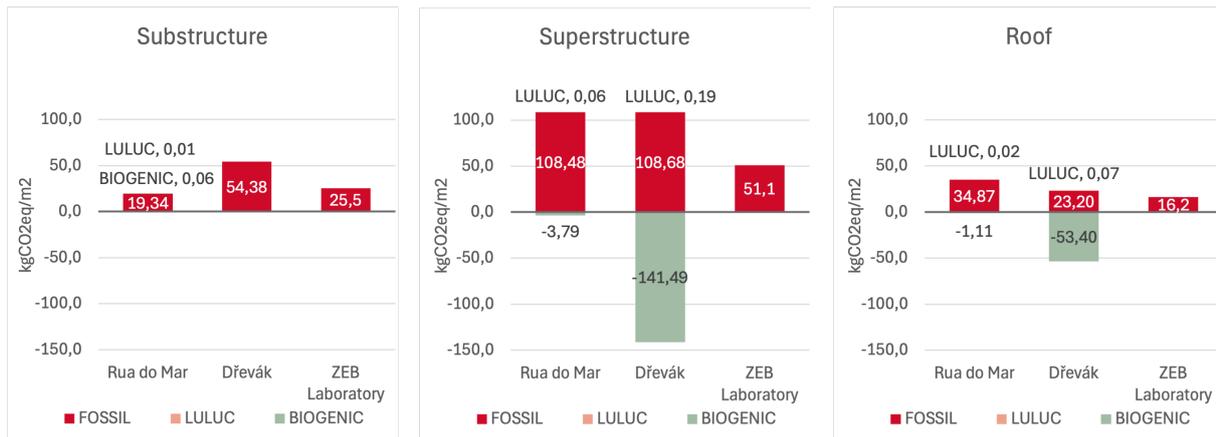
(a) Substructure   (b) Superstructure   (c) Roof

Figure 10: Global warming potential categories – substructure, superstructure and roof.

tial configurations require distinct spans and layouts, influencing the material quantities and structural design.

In the substructure, all three buildings rely on reinforced concrete, resulting exclusively in positive fossil-based emissions. Dřevák shows the highest impact (54.38 $kgCO_2eq/m^2$), which may be attributed to its one-storey underground parking and the use of foundation piles, both of which increase the volume of reinforced concrete. The ZEB Laboratory (25.5 $kgCO_2eq/m^2$), built on a foundation slab, shows higher emissions than Rua do Mar (19.34 $kgCO_2eq/m^2$), likely due to its larger overall size and greater load-bearing requirements.

The roof category presents the clearest difference between material choices. Rua do Mar's concrete roof results in higher fossil emissions (34.87 $kgCO_2eq/m^2$) compared to the timber roofs of Dřevák (23.20 $kgCO_2eq/m^2$) and ZEB Laboratory (16.2 $kgCO_2eq/m^2$). This indicates the advantage of timber solutions in reducing embodied emissions in horizontal (or inclined, as in pitched roof) structural elements. Although Rua do Mar and Dřevák show similar fossil impacts in the superstructure despite using different materials, their roof emissions differ more significantly. This contrast can be explained by differences in LCA system boundaries and modelling approach. In the roof category, all materials – load-bearing and non-load-bearing – are included for both buildings. In contrast, in the superstructure category, the scope differs: in Rua do Mar, infill walls are reported separately under "outer walls", whereas in Dřevák, some of the timber wall elements are load-bearing and therefore included in the superstructure category. This classification affects comparability and may explain why material-related differences are more visible in the roof than in the superstructure.

As one stakeholder (NO8) noted, timber adoption in residential buildings gains additional complexity compared to office buildings:

"...and that [building a timber eight-story apartment building] *was much more challenging because you have different rules that apply when people live there, when it's that high* [has many floors]. *It's a higher*

safety class . . . so, then you have to put a lot of materials outside the wood to make it soundproof enough and fireproof enough. . . " (NO8)

In Dřevák, additional protective layers for fire safety and acoustic standards compliance are included within the Superstructure category in the LCA, which may explain why Dřevák (which adopts timber structure) does not show a greater advantage over the Portuguese case (which adopts concrete and masonry structure), and why its emissions remain notably higher than those of the ZEB Laboratory. This does not imply that timber structures lack carbon reduction potential in the Czech context, but the benefits need to be investigated further, as building use type can significantly influence the results.

Overall, these findings emphasise the importance of considering both biogenic carbon accounting and system boundaries when comparing different structural systems. Excluding carbon storage may lead to the underestimation of the environmental benefits of timber construction, although such benefits are only temporary, as stored biogenic carbon will eventually be released back into the atmosphere at the end of the building's life. Nevertheless, to maintain consistency across cases, comparisons focus on non-biogenic GWP, given the absence of biogenic data for the ZEB laboratory.

While design-stage optimisation is addressed mainly by passive solutions, operational performance is tackled by both passive and active strategies, which are discussed in the following section.

4.1.2 Active systems (Operational strategies)

Active solutions address the building's operational stage (B6), which, together with the production (A1-A3), is the largest contributor to carbon emissions (see Figure 8), and have the potential to reduce them further.

4.1.2.1 On-site energy systems (photovoltaic, solar thermal and heat pump systems)

The main active solution used in all three case studies is photovoltaics. In the Norwegian case, it covers the whole energy demand and allows for the export out of the system boundary. In the ZEB laboratory, shape adjustment was crucial for PV generation and reaching the ZEB-COM, therefore offsetting impacts from construction, operation and materials. In the Portuguese case, the evaluated energy needs, accounting for the compact unit consumption (heating, cooling and domestic hot water (DHW)), are almost fully covered (81 %) by the on-site generation. In the Czech case, approximately a third (33 %) of the energy demand accounting for space heating and ventilation is covered by on-site generation. The energy needs in these two cases are also lowered by the solar thermal panels. However, the energy demand reduced by this solution is not monitored and therefore cannot be evaluated.

The portion of energy needs covered by the on-site production (Figure 11) suggests that even without a special focus on maximising on-site energy generation (e.g. adjusting the building shape) and making it

a priority, a big share of the operational energy demand can be covered on site. However, in the family house, this goal seems to be more realistic than in an apartment building, which could also be caused by the roof-to-useful-floor ratio.
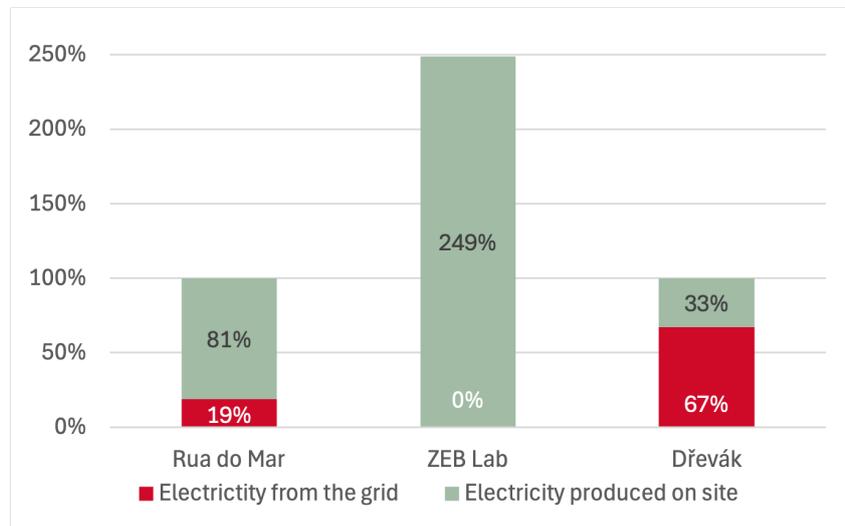
Figure 11: Electricity demand covered by on-site PV generation.

While PV panels contribute to embodied emissions in production (A1-A3 module), also emphasised by one of the stakeholders (NO8), their benefit in the operational stage outweighs the impact in all cases (further discussed in Section 4.3), most dramatically in the Norwegian case study.

The frequency with which the participants (PT9, NO8, NO10) talked about PV systems was unlike that of any other solution implemented in the case studies. The participants' emphasis is reflected in the quantitative data as well – in the Norwegian case study, on-site generation covers all the building's energy demand and achieves energy export.

In the Czech and Portuguese case studies, solar-thermal collectors are used to pre-heat water for heating or DHW and reduce energy demand, whereas in the Norwegian case a heat pump supplies both DHW and space heating (SH). The Norwegian approach covers all hot-water needs without occupying roof area, leaving more space available for PV.

4.1.2.2 Ventilation and heat recovery

Ventilation systems with heat recovery were implemented in all three case studies, but in different technical configurations. In the Portuguese case, the system is integrated with heating and cooling into a compact unit providing also DHW, whereas in the Czech and Norwegian case studies, the ventilation heat recovery (VHR) is designed as a stand-alone solution. Even though this solution reduces the operational energy needs, it is mostly the standard solution applied in new buildings of all use types (PT3, PT15, CZ16) and therefore not stressed as something new or revolutionary. In both Czech and Norwegian cases, the ventilation is the only active measure against overheating, contrasting with the

Portuguese case, where the air-conditioning unit is integrated within the ventilation system, highlighting how the same technical solution can take distinct forms depending on climatic and typological needs.

4.1.2.3 Monitoring

The monitoring system is designed in the Portuguese and Norwegian case studies, while in the Czech one it was mentioned only indirectly. In the first two cases, stakeholders stressed the technical importance (P3, PT15, NO1, NO2): monitoring provides real-time data on energy use, feedback for users' behaviour, equipment performance and indoor environment quality, enabling corrections of unexpected inefficiencies or deviations from values in the standard. For instance, in the Portuguese case study, it revealed unexpected automatic window shutters standby consumption, while in the Norwegian case study, the system showed the heat pump running energy consumption higher than stated by the manufacturer, leading to its replacement. These findings helped the buildings remain within the required limits for the Passive House and ZEB-COM, respectively, demonstrating how monitoring ensures design-performance alignment.

4.1.2.4 Stormwater and vegetation

Stormwater utilisation systems were implemented in all three case studies as a measure to reduce potable water consumption. They include collection, storage, controlled release to the public sewage system (in the Norwegian case study) and on-site rainwater reuse. In the Czech case study, additional stormwater-related measures such as vegetation and green roof were emphasised (CZ12, CZ16) as important for mitigating overheating, reducing the need for active cooling and supporting water management. In contrast, in the Norwegian and Portuguese cases, green roofs were neither implemented nor mentioned as a priority for Passive House or ZEB standards.

4.1.2.5 Phase-change material heat storage

Phase-change material (PCM) heat storage using bio-wax is unique for the Norwegian case study. This solution was implemented as one of the ways to reduce operational emissions and as an opportunity to test a new technology. Although bio-wax PCM systems could, in the future, offer a sustainable method for storing heat over several days, they remain rather experimental.

4.2 National and regulatory context shaping solution adoption

While the first research question outlined the technical measures used in the case studies, this section explores how national, climatic and other contexts shape their adoption and prioritisation. Even equivalent solutions can be implemented for different reasons, take different forms and face distinct challenges

depending on the national context. Contextual factors influence not only which options are adopted, but also their cost and overall feasibility. They also affect which solutions are prioritised or emphasised over the others.

With the second research question, we ask *"What impact do national and climatic contexts have on the technical and construction solutions adopted in the case studies?"*.

4.2.1 Climatic and comfort factors

The topic of climatic conditions and related aspects emerged in discussions with stakeholders in all three countries. As most Portuguese stakeholders (PT3, PT9, PT14, P15) mentioned, many houses in Portugal can be uncomfortable – cold and humid in winter and hot in summer – which motivates users to seek better solutions. The Passive House standard states clear guidelines for airtightness in combination with the continuous insulation layer, which is envisioned (PT3, PT14, PT15, PT17) as an ideal standard, achievable in the Portuguese context:

"We like the Passive House because it has a clear goal with clear parameters, with very clear criteria. And that was what we were looking for. Performance, that could allow us to have the maximum comfort, the maximum well-being with the least energy consumption." (PT3)

This suggests that in warmer climates, where a comfortable indoor environment in colder seasons is not addressed as a standard practice, comfort-driven motivation may be more influential than regulatory incentives.

In the discussions with Czech stakeholders, where the climate is colder than in Portugal, the concern was cooling rather than the already established heating. Climate change and rising temperatures place growing emphasis on mitigating overheating and, therefore, on operational costs for cooling:

"If temperatures keep rising according to the predictions, as they currently do, we'll have to start thinking not only about saving energy for heating, as we did in recent years, but also how to cool buildings during the summer." (CZ12)

The company's strategy addresses this problem through passive solutions such as shading and green roofs, which also mitigate heat island effects:

"We try to use green roofs – with a thicker build-up – which help prevent overheating. If the building doesn't overheat, there's no need for active cooling in the summer. So, we aim to design buildings in a way that avoids creating secondary energy demands." (CZ16)

The green roofs or heat islands effects were not discussed by stakeholders in the other two countries, highlighting how local climatic priorities determine which measures are prioritised.

Regarding the indoor environment comfort, some Norwegian ZEB Laboratory users (NO2, NO6) implied

that active cooling would be beneficial on hot summer days.

In the Czech and Norwegian case studies, the airtightness and continuous insulation layers were not stressed during the interviews. Only one participant (NO10) mentioned that the solution for the Norwegian case study used thicker insulation than is the standard for new construction, but it did not emerge as one of the main topics. As the Norway is the coldest out of three countries with 3587 HDD, the insulated building envelope seemed to be a standard solution and did not represent any challenge in design or construction of the case study building, as well as in Czechia, with lower number of HDD (2645), where thermal insulation and quality of building envelope is evaluated as a standard procedure (CZ12).

In these two case studies, the debate on insulation shifted from thermal performance to acoustics because of the timber structure. It shows the context (timber adoption) changes what aspects of insulation and other solutions are even discussed and how the same technical measure (insulation) acquires different roles:

"Eventually, the limiting factor wasn't fire safety, but acoustics – so we had to make it [the structure] *slightly thicker for sound insulation."* (CZ16)

4.2.2 Knowledge and construction culture

Although the Passive House standard provides clear design parameters, execution remains challenging in Portugal, where specialised knowledge and skilled labour are not yet widespread. As a result, the design is difficult to replicate and correctly implement on-site without specialised guidance, which increases the cost. The on-site execution was a major barrier in the Portuguese case study, and, according to stakeholders, continues to be a challenge in construction practice beyond the case study. Limited design expertise was also mentioned in the link with ventilation systems, as it may lead to oversizing and unnecessary costs, as one of the stakeholders observed:

"And the common mistake is about the ventilation system. It's not well designed . . . you invest a lot of money and at the end, you don't have the ventilation system that is working in a good way. . . " (PT15)

In Czechia, the lack of expertise shifted attention toward the construction and waterproofing of a timber structure. Limited experience made the design and execution of the timber structure more problematic:

"Then there's also the topic of moisture and water . . . The first issue we ran into was finding the right designer with the necessary skills and experience." (CZ16)

This uncertainty also affected the construction scheduling – even specialised timber construction companies tended to propose longer construction periods (CZ16), which contributed to higher construction costs. This highlights how intentions (timber innovation) can interact with knowledge gaps, producing learning opportunities but also risks and implementation delays.

In Norway, no obstacles to the timber adoption and achieving to higher energy efficiency have arisen in the discussions.

4.2.3 Economic and motivational drivers

In Portugal and Czechia, according to interviewed stakeholders, the operational cost and unstable geopolitical situation with the gas (energy) delivery, respectively, were mentioned as two of the drivers promoting clients' interest in passive solutions and PV panels for on-site energy generation (PT14, CZ12). On the contrary, low energy prices (PT14) in Norway may cause the economic factor to be a weak motivator, and some stakeholders there framed the sustainability (NO8, NO10) or taxonomy advantages (NO8) as drivers instead. The statement of the passive house certifier (PT14) shows why particularly Passive House may not be a very motivating ambition in Norway:

"For example, in Norway, there are very low energy prices, very low. So, there's not so much need to save energy. And then we had some groups [Norwegian stakeholders] that visited the Passive Houses, but I don't think anything came out of it." (PT14)

When the building envelope is airtight and insulated, and some insufficiencies can be mitigated by higher energy expenditure for heating, the focus can gradually shift from energy savings alone to the choice of materials and the overall carbon footprint. In the Norwegian case study, however, operational costs were likely not addressed because of the building's specific use type – the ZEB Laboratory operated by a research centre – which was a part of a research project with an extended budget and objective to test innovative solutions while achieving the ZEB-COM target.

The motivations of clients and future building owners to implement energy- and carbon-efficiency measures differ across national contexts. Stakeholders reflected on these motivations not only in relation to the case studies but also from their wider professional experience. In Portugal, the main motivators for the clients mentioned were energy bills and comfort, in Czechia, energy security and independence, and in Norway, values-driven sustainability. For the interviewed stakeholders, however, the motivation was consistently sustainability. Given the limited number of interviewees, these observations should not be treated as nationally representative, but rather as a starting point for further discussions.

While contextual challenges differ, similar measures are often applied to mitigate them. One example is stormwater reuse – a solution implemented in all three cases but driven by different motivations. In Portugal, stormwater reuse was a part of the WEFI building concept (for the concept definition see Section 3.1.1). Although not yet widely recognised, recent water shortages in southern regions of Portugal increased public awareness of water use optimisation. In Czechia, on-site stormwater capturing is designed to help mitigate urban heat islands and is also perceived as a way to reduce energy demand. In the Norwegian case study, it primarily served as a means of reducing emissions, although one participant (NO2) noted that the reused stormwater could be utilised more efficiently.

4.2.4 Legislation and policy

The following sections examine how legislation and policy frameworks shape the adoption of low-emission building solutions across the studied contexts. The discussion covers regulatory aspects related to timber construction, the Energy Performance Certificates (EPCs), and the role of EU-level policy.

4.2.4.1 Timber regulations and fire safety

Since only the Czech and Norwegian case studies employ the timber structural solution, interviews with Portuguese stakeholders did not include discussions on this structural material. In both Norway and Czechia, legislation constrained the adoption of timber structures through requirements such as height limits[20]. Apart from the stricter height limit for timber buildings, these regulations apply equally to all construction types. However, meeting them is generally more demanding for timber structures, as wood is perceived as a higher-risk material (CZ13, NO8). This perception makes their adoption more challenging and consequently more expensive.

Fire safety and acoustic performance requirements may also entail the addition of extra materials to comply with regulatory thresholds, which can partially offset the embodied-carbon advantages of timber construction. For instance, the use of gypsum boards with high embodied carbon or additional acoustic insulation may be required to achieve compliance in fire safety and acoustics, respectively.

In Czechia, a solution for fire safety compliance was found through an alternative calculation approach (CZ16), which allowed the structure to meet the regulations without increasing thicknesses or adding unnecessary materials. For acoustics, however, some additional thickness to comply with the standard threshold was necessary.

The viability of timber as a structural solution, therefore, depends not only on technological and economic feasibility but also on how differences between structural systems are addressed within legislative frameworks and on the willingness of regulatory authorities to accept approaches deviating from standard practice. Hence, regulation shapes not only feasibility but also perceptions of risk and cost, affecting how timber is positioned in each market.

4.2.4.2 Energy Performance Certificate credibility and limitations

The rating of Energy Performance Certificate (EPC) is common for all EU countries and Norway as well. However, in Portugal, one of the stakeholders mentioned that having great performance according to the

---

[20] In Czechia, the height limit for wooden buildings was previously up to 12 m and was recently extended to 22,5 m if fire safety is verified through calculations rather than prescriptive norms (Kuklík and Gregorová, 2025). In Norway, height limits are generally determined by municipal zoning plans, while compliance with the national building code (TEK17) sets requirements for fire safety, structural stability and acoustic performance (Direktoratet for byggkvalitet, 2017).

national regulation does not ensure the comfort and efficiency of the building:

"It obtained the maximum rating in the energy balance assessment – the national mandatory energy assessment – but that doesn't mean that we are going to have an efficient building or that we are going to have, in the end, a comfortable building. . . " (PT3)

A concern raised by Czech stakeholder (CZ12) was about the common clients' misconception that the EPC label states the real energy consumption – equal to the energy bills – which sometimes may lead to the clients' confusion and feeling that the EPC labels are ineffectual:

"And the certificate can't do that [reflect the users' (plug-in) consumption] *– it's meant to compare buildings technologically one with another – how the user behaves isn't included."* (CZ12)

4.2.4.3 Top-down policy and EU influence

In the building sector and energy efficiency of buildings, the top-down structure is established from the EU level and among the interviewed stakeholders (PT4, PT9, PT14, PT17, CZ12, CZ13, NO9) was seen as a great enabler for efficient buildings. Although the economic aspect is to some extent hindering the change, and the misconceptions of the public may cause lower demand for the energy-efficient solutions, the legislation and subsequent transposition into the national legislation promoted the change. Companies are forced to find ways to stay competitive while reaching certain climate goals. The problem may arise when the national transposition is adopted with insufficient consultation with stakeholders directly involved in the construction sector. A member of the Concerted Action – Energy Performance of Buildings (PT9) expressed that the involvement of the stakeholders even before the national transposition of the EU regulation is important, because sometimes the experts do not understand the EU regulation in the national context and therefore cannot promote efficient change in the construction sector in their country:

". . . we will have the consultation process . . . with many stakeholders. . . . So they understand a little better why those requirements are in the EPBD and specifically what the positive impacts are from implementing them. . . . At the end, the transposition, not only is it not new, but it's as adjustable for the Portuguese context as possible." (PT9)

4.2.4.4 Demonstration effect

The demonstration of examples in practice is important to show the effects on the housing, comfort and energy and promote the down-top structure.

In Norway, the ZEB Laboratory serves as such an example, and stakeholders from Czechia hope that the "Dřevák" will as well. However, the emphasis on pilot buildings is placed more on timber construction in Czechia, and on the implementation of technical solutions to achieve the ZEB-COM ambition in Norway,

rather than on comfort and quality of life, which may not be a primary motivation for the average user in these two countries.

Across all three countries, stakeholders (PT3, PT14, PT15, CZ12, CZ16, NO8) emphasised the effect of demonstration – when pilot buildings and examples exist and their performance is transparent, the risk declines and adoption becomes more likely. In Czechia, large developers slowly adopting timber as a structural material can serve as reference projects; in Norway, pilot buildings funded as research projects (similar to ZEB Laboratory) are already present; in Portugal, widespread examples that would show people – potential clients – that and how the Passive House works would help to promote change (PT15). According to one Portuguese stakeholder, this should include not only built examples but also a global monitoring platform that shares real building performance data, which would help spread the knowledge and build trust:

"It's crazy because you buy a car, you know the consumption ... or any kind of device. You buy a building, you don't know anything ..., we should have a monitoring platform worldwide. ... let's see ... if it is comfortable or not – how much is the energy consumption, concerning heating or cooling, water ... we are monitoring all the Passive Houses certified in Portugal and we allow everyone to go there and to search and to believe by seeing." (PT15)

One interviewee (PT3) even suggested that requiring public buildings to meet the Passive House standard could help resolve this issue[21].

4.2.4.5 Procurement model and ownership scheme

Both policy-level frameworks and project-level collaboration influence the successful delivery of energy-efficient buildings. Stakeholders in Portugal and Norway (PT14, PT15, CZ16, NO1, NO8, NO11) emphasised that close cooperation among disciplines was essential for achieving set performance ambitions, particularly in unfamiliar contexts.

In the Portuguese case, the collaboration between designers and the construction company was based on mutual agreement rather than a formalised procedure, while in the Norwegian case an integrated project delivery (IPD) model was adopted. IPD enabled all professional teams to work together from the early design phase. This approach facilitated compromise, aligning with the professions' ambitions and requirements while maintaining the overall energy and emission goal.

Stakeholders (PT4, NO8) also highlighted the ownership scheme as a determining factor shaping motivation for energy efficiency. For individual homeowners, operational cost reduction can serve as a strong motivation even without an explicit sustainability vision. However, for larger projects – where the developers build to sell and do not benefit from reduced operational energy costs – motivation must instead arise from regulatory requirements or corporate sustainability commitments.

---

[21]e.g. as in Spain, where it is set for all new social housing.

As the economic aspect of energy-efficiency measures can hinder implementation, increasing buyers' awareness and market understanding becomes crucial to create demand for sustainable solutions and to offset the unfavourable economic position of developers.

4.3 Transferability of the measures across different contexts

The third research question examines how solutions adopted in the three case studies can be transferred across national contexts and what barriers and challenges may arise. In contrast to the second research question, which focused on the context influencing solution selection, this section evaluates whether – and under what conditions – those solutions can be transferred.

The question is ***"What challenges and opportunities influence the transferability of the solutions identified in the case studies to different contexts?"***

4.3.1 Structure

Building on findings discussed in Section 4.1.1.2, the use of timber structure in case studies across distinct climates (Norway – Nordic, Czechia – Continental) indicates that the climatic differences do not pose technical constraints. Instead, national regulations, construction practices and market perceptions continue to influence feasibility.

Although timber is generally associated with lower embodied emissions, LCA results show that the embodied emissions of the Czech timber superstructure are similar to those of the Portuguese super-structure based on concrete and masonry.

At the same time, the share of embodied emissions (A1-A3) relative to operational emissions (B6) is comparable in the Czech and Norwegian case studies (see Figure 8) despite the differences in national electricity mixes (Table 5 in Section 2.7.2). This ratio is notably higher in the Portuguese case, where conventional concrete dominates over operational energy share.

This contrast suggests that structural material choice alone does not directly result in lower embodied emissions (as seen in the Czech-Portuguese comparison; e.g. Machado *et al.* (2025)), but it can contribute to a more balanced relationship between embodied and operational emissions when combined with energy-efficiency and low-carbon solutions. Therefore, although the timber remains a potentially valuable strategy for decarbonisation, its benefits are likely dependent on building typology, regulatory requirements and system boundaries. The quantitative effects and transferability across contexts cannot be established based on the evidence from this study.

Different RSPs (Norway 60 years; Czechia 50 years) appear to have only a limited effect on these shares, even though structural materials are assumed to have an reference service life (RSL) equal to

the RSP in both cases (therefore longer RSL in the Norwegian compared to the Czech case). To avoid additional inaccuracy, the results in the graphics are reported in $kgCO_2eq/m^2$ rather than $kgCO_2eq/m^2$

Beyond legislative frameworks discussed in both Czechia and Norway – which impose similar constraints on timber structures – the key differentiator is the set of misconceptions surrounding timber buildings. In Czechia, one stakeholder (CZ16) reported that users and clients often expect timber structures to be faster to build, more slender and – above all – cheaper. The share of newly built timber buildings in Czechia has risen since 2000 (Borovcová, 2023) and awareness of this construction type may therefore be increasing. However, the available statistics cover only family houses, for which, as mentioned stakeholder noted (CZ16), the reality of faster and cheaper construction may hold. Demonstration projects in other typologies (e.g. apartment houses or non-residential), combined with transparent communication to the public, could help dispel these misconceptions. These unfulfilled expectations may influence buyers' perception and public acceptance of timber buildings; however, empirical validation is outside of the scope of this study.

Norwegian stakeholders did not express any problems due to the structural material choice in terms of knowledge or skills, unlike in Czechia, where timber buildings are rather constructed as family houses and this project is the largest residential building in the country (CZ12), which caused complications and revealed the presence of a knowledge gap. Although encountering problems, the solution exists, and the competition company was willing to share its solution for the same problem, and the fire safety authorities were willing to accept a different solution than the common one embedded in standards (CZ16). The peer exchange among practitioners can offset knowledge gaps more efficiently than formal regulation.

4.3.2 On-site energy generation and storage

When the two already in-use case study buildings were designed, the nZEB requirement introduced by the 2010 EPBD recast (European Parliament and Council of the European Union, 2010a) had only recently entered EU law and was yet to be transposed into national regulations (mandatory for public buildings form 2019 and all new buildings from 2021). Accordingly, integrating on-site generation in those two projects was voluntary at the time. Under the 2024 recast, the focus shifts from renewable quotas to solar-readiness and deployment of solar systems where feasible (European Parliament and Council of the European Union, 2024). Consequently to the EPBDs, the discussion today concerns not the transferability of PV integration but rather its feasibility, suitability for local conditions and the factors influencing its effective implementation.

Stakeholder interviews confirmed that photovoltaic is the most widely recognised on-site renewable solution – even among the general public – and together with solar thermal panels is more feasible than alternatives such as heat pumps. As one participant (CZ16) explained:

"The only thing we're currently not doing is heat pumps, which still seem economically unviable from our

point of view. So, the "pond" we can draw from for more innovative solutions isn't very big." (CZ16)

This comment referred to an apartment building context, suggesting economic feasibility may vary across building types. Another participant (PT14) highlighted the social and financial dimensions of PV adoption and Passive House concepts:

"That [motivation] *depends on the background of the client. ... We have poor people, who look at the low running costs."* (PT14)

However, upfront PV implementation cost can remain a barrier for some owners. National transposition of the EPBD (e.g. allowing solar readiness where immediate installation is not feasible) and financial support schemes at the national or municipal level may therefore influence transferability at the project scale, rather than national or climatic context. This remains a hypothesis, as the Portuguese and Czech case studies did not explicitly rely on subsidy schemes to meet nZEB or Passive House targets and the Norwegian case is not representative of typical market projects, as it was developed within a research programme.

Using PV in varying contexts and the on-site generation implemented in 2010 EPBD suggests that the solution is broadly transferable across climate zones. To put these perspectives in context, the waterfall charts in Figure 12 visualise the effect of PV systems on total life-cycle GWP (fossil + LULUC), comparing case studies built in three different contexts. The "Baseline – no PV (B6)" represents the operational emissions without renewable energy contribution. Together with production and replacements (A1-A3, B4), transport (A4) and installation (A5), these form the total emission burden, followed by the offsetting contributions from operational benefits (B6, D).

The analysis shows that active solutions – even those with a carbon-intensive production stage – can significantly reduce overall emissions, either on-site or through exported energy, regardless of climate zones. In Rua do Mar, PV generation offsets a considerable share of operational emissions. In Dřevák, a similar relative offset is achieved, however, the initial operational emissions are higher, likely due to the building's energy supply (electricity + natural gas) and the national electricity mix. Consequently, the net GWP remains higher (121,6 $kgCO_2eq/m^2$).

The ZEB Laboratory demonstrates the strongest effect, where operational energy offset combined with exported energy credit results in a negative total (-341,6 $kgCO_2eq/m^2$). Accordingly, its PV-related embodied emissions (A1-A3, B4) are several times higher than in the other two cases, as the PV panels form a significant part of the building envelope.

The "net-zero" balance may not always translate into real-life benefits, as the periods of highest PV production often overlap with periods of lowest building energy demand. With cooling already needed in Portugal and cooling demand expected to rise in Czechia, the surplus electricity generated during summer may increasingly be used to cover cooling needs in countries with similar climatic conditions, further enhancing the benefits of PV generation. Even in the colder Norwegian climate, similar patterns

(a) Rua do Mar (b) Dřevák (c) ZEB Laboratory
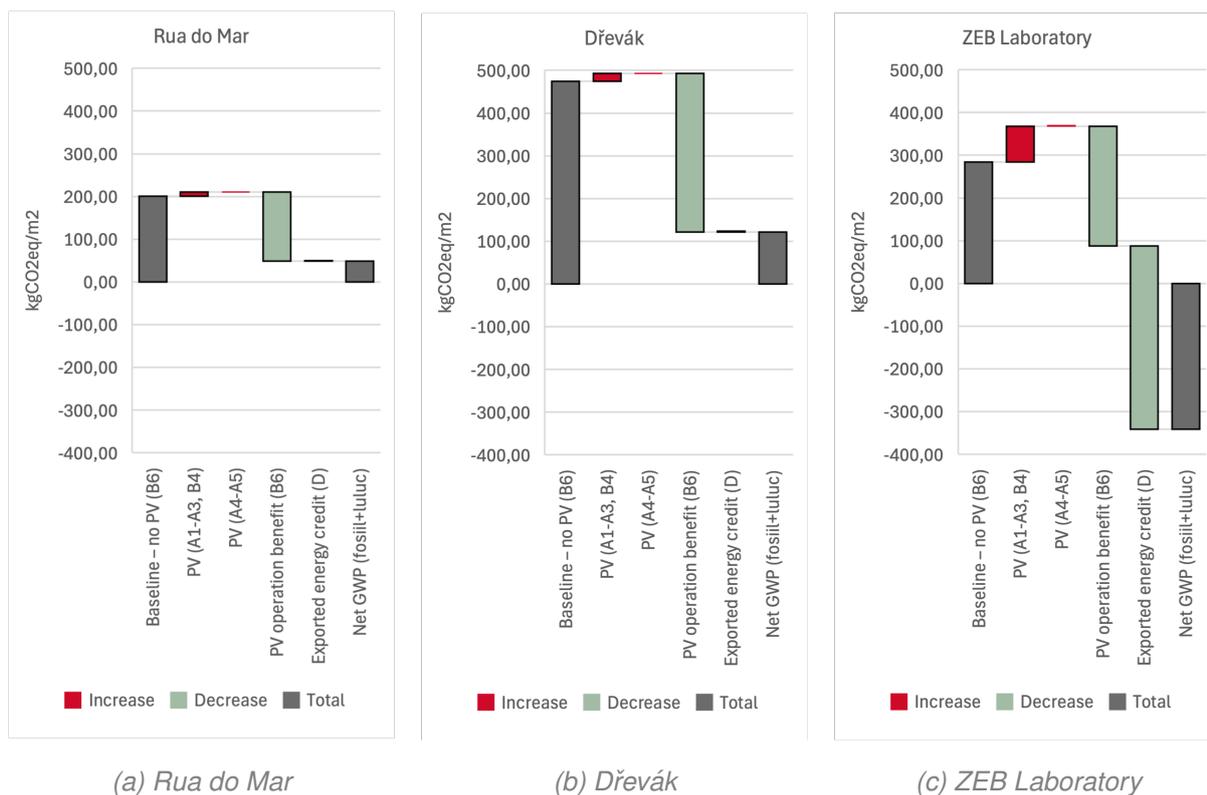
Figure 12: Emission contribution and reduction of photovoltaic systems.

in existing buildings were mentioned:

"...even in Norway ... We sometimes use more energy for cooling than for heating – in some other buildings." (NO1)

The current mismatch may therefore be levelled in the future. phase-change materials (PCMs) heat storages offer short-term heat storage that can smooth daily heating peaks, however, they do not address the seasonal mismatch between PV generation and electricity demand and their relevance for energy balancing in varying contexts remains limited.

While the share of embodied emissions is comparable across cases (see Figure 8), differences in national electricity mixes (see Section 2.7.2) mean that the potential carbon benefits of PV-generated electricity will vary. In Norway, where the electricity mix is largely renewable and thus less carbon-intensive, the emission offset per kWh is expected to be lower than in Czechia or other countries with more carbon-intensive grids.

Local regulations on building position, orientation or even shape can limit solar exposure in some municipalities. However, in the Portuguese case study – despite orientation constraints – a substantial share of electricity demand was still covered by PV generation. This indicates that such municipal-specific rules are not, on their own, a barrier to adoption, and that perceived regulatory barriers are often overstated. Within existing frameworks, meaningful PV deployment remains achievable.

In interviews (PT9, PT15, CZ12, CZ16, NO1, NO10) across all three countries, the topic of on-site generation solutions was discussed, and no specific context-dependent technical barriers were identified. However, in Czechia, the heat pump option for space heating was described as technically feasible and potentially advantageous if future space cooling is needed, but not yet economically viable (CZ16).

4.3.3 Monitoring system

The implementation of the monitoring system showed significant importance, and no barriers to the implementation were mentioned, apart from additional cost. However, this cost, especially in small buildings such as family houses, is around 10 % extra (P15) in a trade for important data. Monitoring systems, therefore, appear universally transferable, as cost scales with complexity, not context.

4.3.4 Stormwater utilisation and green roofs

Stormwater systems appeared broadly transferable across contexts, as no stakeholder reported clear technical or regulatory barriers. Only the Czech case included a green bio-solar roof. Although using this solution in only one case limits direct comparison, no constraints were identified. Differences resulted primarily from local motivation and site-specific conditions rather than technical feasibility or nationally dependent aspects. For example, one Norwegian stakeholder reflected:

"I think we also could have made much more of the stormwater runoff system and better utilise the water in that tank." (NO2)

In this instance, the ZEB Laboratory's mostly paved surroundings, with a low amount vegetation requiring irrigation, likely limited opportunities for stormwater reuse and reduced its potential for emission reduction. Overall, while stormwater reuse and vegetation-based strategies are likely technically applicable across contexts, their relevance varies depending on the building site characteristics and local priorities.

4.3.5 Cooling and ventilation

Ventilation and cooling strategies were context-dependent but generally considered technically feasible in all three case studies. VHR was described as mostly standard or commonly applied solution (PT3, PT15, CZ16).

5. Discussion

5.1 Purpose and structure of discussion

This chapter integrates quantitative results (LCA) and qualitative stakeholder insights to interpret and summarise why high energy-efficiency and low-carbon solutions perform, and are adopted, differently in different contexts. Most measures are already established rather than novel, but their implementation varies depending on social, economic, and regulatory conditions.

The discussion is organised as follows: first, an overview of solutions implemented across the three case studies (RQ1); second, the contextual factors that shaped adoption (RQ2); third, which of these solutions are transferable and under what conditions (RQ3). The chapter concludes with limitations.

5.2 Technical and construction solutions adopted – RQ1

The case studies demonstrated a consistent set of passive and active strategies. Passive solutions included early-stage optimisation (form, compactness), airtightness, improved insulation, material selection, and vegetation and green roof, where relevant. Active measures comprised PV systems, monitoring, stormwater reuse, and, in one case, experimental bio-wax PCM heat storage.

The findings show that, while the majority of these measures are well established, their effective implementation depends on coordination across design stages. The extent of adoption varied according to economic, regulatory and climatic context (see Section 5.3).

5.3 Contextual influences on adoption – RQ2

Differences in adoption across contexts, as identified in the stakeholder interviews, were primarily associated with four dimensions: economic and market conditions, regulatory settings, professional collaboration and socio-cultural factors – including variations in knowledge, awareness and common misconceptions. These dimensions align with the barriers identified by Ürge Vorsatz *et al.* (2020) (see Chapter 2.2.3). Additional factors, such as ownership schemes and climate, further influenced how solutions were prioritised and implemented.

5.3.1 Economic and ownership drivers

According to stakeholders, ownership models influence the priorities and motivations to adopt energy-efficient solutions. When buildings are intended for owner-occupation, operational cost reduction can serve as a driving force, often independent of sustainability goals. In contrast, in developer-led projects built for sale, investors do not benefit directly from long-term energy savings, which reduces the motivation. In such cases, regulation or corporate sustainability ambitions become more important drivers.

In larger, developer-led projects, financial pressure tends to fall on developers, whereas in smaller projects, such as family houses, it falls on homeowners. For developers, additional costs were related to technical solutions and extended coordination and building times resulting from deficiencies in knowledge and expertise, and the need for additional supervision. Homeowners may face economic pressure arising from technical solutions, limited awareness and absent professional guidance, resulting in late-stage optimisation.

Some stakeholders also emphasised that while certifications (e.g. EPCs, BREEAM, Passive House) can simplify communication with clients and the public, full certification or the highest EPC grading is not the only meaningful pathway. Gradual improvements – such as choosing lower–carbon materials or resolving minor technical deficiencies – still contribute to emission reductions without imposing additional economic burden on homeowners or developers motivated by sustainable visions.

Increased construction costs for high-performance solutions, such as PV panels or solutions such as timber construction, are not reflected as a market advantage, likely because the advantages, such as lower energy bills or reduced emissions, are not yet fully recognised in market demand. Existing regulatory frameworks should be complemented by market education. As buyer awareness grows, the demand for sustainable solutions may follow, creating the motivational aspect for developers.

5.3.2 Policy and regulatory conditions

Regulation was perceived as both an enabling framework and a practical constraint. While EU-level directives prompt shared standards and knowledge, their effectiveness depends on national transposition. Communication between policy makers and practitioners can ensure that the transposition is well understood and functional in practice. Organisations such as Concerted Action – Energy Performance of Buildings (CA EPBD), help facilitate such cross-silo dialogue, guaranteeing the regulations are adapted to the national context.

More significant challenges occurred at the local level. Municipal regulations – especially constraints on building height and orientation – impacted the optimisation of solar exposure for active solutions such PV systems and solar thermal panels, but also passive design such as balancing summer and winter heat gains. Nonetheless, national authorities were open to alternative approaches (e.g. fire safety calculation method instead of standard values, integrated project delivery), demonstrating increasing institutional

willingness to accommodate innovative solutions.

Although the legislative aspect was frequently discussed, its impact on the adopted solutions is rather limited. It posed additional constraints during the design and even construction stage and influenced design outcomes, however, it was not a prohibitive barrier.

5.3.3 Knowledge, construction culture and collaboration

Embedding collaborative procurement models among standard contract procedures could reduce uncertainty, enhance communication and facilitate the delivery of low-carbon outcomes more effectively.

Collaboration emerged as an important enabler for achieving high-performance ambitions, especially when the solutions applied are not well-established practices in the country (e.g. airtightness in Portugal, large-scale timber structures in Czechia and ZEB-COM in Norway). Smaller projects may rely on informal cooperation, while complex ones may benefit from formal collaborative procurement models such as IPD. IPD establishes the relationship between the parties, ensuring collaboration from the early design stage, aligning objectives and sharing financial responsibility.

However, early involvement of multiple professionals increases design-stage cost, making such models suitable primarily for larger, ambitious and more complex projects such as ZEB Laboratory. In Norway, legislative bodies are already working on the formalisation of IPD-type approaches. Formalising collaborative procurement models could accelerate the adoption and help mainstream ambitious, low-carbon buildings.

5.3.4 Climatic and technical context

Climate was perceived as an aspect shaping the priorities, rather than the feasibility. Portuguese stakeholders discussed airtightness and optimised insulation layer, Czech and Norwegian stakeholders focused on other aspects of construction.

Aligning with findings of Ürge Vorsatz *et al.* (2020), this study also found that the technical feasibility was not perceived as a major barrier. The limitations mentioned by stakeholders were attributed to insufficient practical experience rather than technological constraints themselves. Geographic barriers were not even mentioned by stakeholders, confirming it as the least emphasised aspect (Ürge Vorsatz *et al.*, 2020).

Overall, contextual factors shaped the barriers, motivations, level of performance, and design priorities rather than technical feasibility. Collaboration and knowledge exchange were repeatedly cited as effective means of overcoming the constraints.

5.4 Transferability of effective solutions – RQ3

This section discusses the transferability of the technical solutions identified across the case studies and the extent of context-dependent aspects influencing it.

5.4.1 Transferable and context-dependent measures

The discussion is structured according to the type of solutions – passive measures, active systems and innovative systems.

5.4.1.1 Passive measures

Passive strategies such as high-performance windows, airtightness and a continuous insulation layer appeared to be technically transferable across all three contexts and, with the exception of airtightness in Portugal, were commonly implemented. By contrast, early-stage optimisation of building form and orientation was limited by local regulations.

A green roof was adopted only in the Czech case, and since no technical constraints were reported, absence in the Portuguese and Norwegian case studies appears to reflect project priorities rather than feasibility. In Rua do Mar, water retention was addressed through the garden space, while, in the ZEB Laboratory, the roof area was allocated to PV panels to maximise on-site generation.

5.4.1.2 Active systems

PV systems proved to be one of the most universally applicable solutions, performing well in both cold and warm climates. In regions where heat island effects mitigation or stormwater capture is needed, they can be combined with vegetation in "biosolar" roof configurations while providing on-site energy generation.

Although solar thermal panels were not implemented in the Norwegian case study, and their viability in cold climates cannot be confirmed here, stakeholder insights suggest that on-site generation systems in general are technically transferable across contexts. However, the extent of their environmental benefit depends on the local electricity mix (grid emission intensity), building energy demand and economic or regulatory conditions.

Active cooling is not yet perceived as necessary in climates with a lower number of CDD, but several stakeholders suggested it may become increasingly relevant as temperatures rise. Although the observations indicate that both active cooling and VHR systems are technically feasible across climates, knowledge and expertise gaps in some contexts can lead to an inefficient design. This can further contribute to the misconceptions that Passive Houses and energy-efficient buildings are significantly more

expensive than conventional ones and thereby hinder a wider adoption.

In the Czech case, one stakeholder noted that water-based heat pump systems used for low-temperature floor heating could be configured to provide active cooling in the future and considered this a promising solution. This suggests that in contexts where the concept of floor-heating is already established, such systems could be adapted to meet future cooling needs arising from climate change.

Monitoring systems were identified as highly transferable and valuable for performance tracking and understanding occupants' behaviour. Since their cost is relatively low compared with the total construction cost, their adoption may depend more on developers' motivation than on technical or financial constraints. With growing awareness, monitoring could also evolve into a marketing strategy.

5.4.1.3 Innovative systems

Bio-based PCM heat storage remains an experimental measure, currently limited more by market readiness than by climatic or technical feasibility. As it is not commercially available, its adoption would likely increase project cost and therefore reinforce existing economic barriers even for typologies that could benefit from thermal storage capacity.

5.4.2 Role of building typology

Building typology influences both the selection and extent of implemented measures – socially (in terms of knowledge), technically and economically.

In single-family houses, direct client involvement often supports energy-efficient design. However, informed decision-making can be hindered when professionals fail to present viable options early in the design process.

Beyond user-related aspects, the physical characteristics of a building also play a determining role. As implied by one of the stakeholders, the energy needs to be covered by on-site generation in office buildings are high due to all the technology used in the building. In the ZEB Laboratory, it was necessary to adjust the building's shape to reach the ZEB-COM target. The roof-to-floor area ratio affects PV generation potential, while structural systems – such as the use of deep or shallow foundation or inclusion of underground parking – directly influence embodied emissions. Consequently, typology shapes the challenges when adopting "non-conventional" structural materials such as timber, where feasibility depends on both structural design and regulatory acceptance.

Moreover, certain building typologies are associated with different ownership schemes, which, as discussed in Section 5.3.1, can further influence the motivation to reduce operational impacts.

In conclusion, building function and typology affect the transferability of both passive and active solutions

to the same extent as the national context.

5.4.3 LCA synthesis

Comparative LCA analysis in this study illustrates the importance of a holistic view when assessing building performance and allocating the focus for improving it.

5.4.3.1 Material and methodological insights

The results indicate that the relative benefits of timber structures depend strongly on both methodological and contextual factors. In one case, timber did not exhibit a significantly lower fossil GWP than a concrete structure, which could be attributed to national energy mixes or differences in the LCA scope and typology. Nevertheless, the biogenic carbon stored in timber remains a significant, yet only temporary, advantage, even when it is not reflected in the fossil-impact LCA results.

Stakeholders further noted that LCA comparisons remain challenging, particularly when assessments are conducted at different times or under differing national frameworks. Variations in system boundaries, evolving databases and changing emission factors may lead to inconsistent outcomes, which discourage innovation and undermine the perceived credibility of low-carbon solutions when their performance appears similar to conventional buildings. The issue lies not in the tools themselves but in the insufficient harmonisation and consistent interpretation across LCA frameworks. These findings reinforce the need for greater consistency and transparency in comparative assessments, as also discussed in Section 5.5.

5.4.3.2 Added value of qualitative synthesis

The LCA as a quantitative tool is useful when comparing two buildings, however, the scope and place in time are major limitations of cross-country comparisons and may even become irrelevant. Therefore, integrating stakeholders' insights with LCA results helps explain not only what performs differently in distinct contexts but also "why". While numerical comparisons alone cannot capture the human and institutional factors, the qualitative insights reflect how decision-making awareness and regulation shape the outcomes.

5.4.4 Design and implementation

Even with solid design and planning, implementation can be constrained by current construction practices in different countries. While design principles such as airtightness and orientation are universally applicable across contexts, ensuring their performance depends on local construction culture and may require enhanced supervision and quality assurance. According to Portuguese stakeholders, although the Passive House standard was not – and it is still not – widespread, materials and equipment for both

passive and active solutions were available at the time of construction, and their availability did not pose a significant barrier. Even where longer transport distances are required, the additional impact would primarily affect Module A4 (transport), which, based on Figure 8, is small relative to A1-A3 (product stage).

5.5 Limitations and their implications

The limitations identified in this study are connected with both the quantitative (LCA) and qualitative components of the research.

5.5.1 LCA-related limitations and data constraints

The comparability of the LCA results was limited because the assessments were conducted by different assessors using different tools. Consequently, the scope and methodological boundaries differed in several aspects: the allocation of the PV benefits, the exclusion of biogenic carbon in the Norwegian case study, the construction stage (A5) being represented only by the data included in EPDs in the Portuguese case study – whereas the other two cases included additional site-specific activities, such as machinery and groundworks – and the use of different reference study periods which affected normalisation.

The data for the LCA modelling of the Rua do Mar family house were incomplete in several areas. A large portion of EPDs used was for similar, but not the specific products. Many materials used on site were recorded in the list of quantities only by generic name, which increases the uncertainty whether the specific products matched the EPDs applied. The lack of local EPDs required the use of data from products manufactured outside of Portugal, which may have influenced the overall emissions levels.

The results should therefore be interpreted as indicative rather than strictly accurate, which limits the validity of cross-case comparisons. In some instances, such comparisons may even discourage the adoption of solutions that did not demonstrate substantial benefits, or may even disadvantage the companies involved.

5.5.2 Conceptual limitations

The research was also limited by the availability and characteristics of the selected case studies. The three buildings differed in typology (scale and function) as well as in the time of construction, which may have influenced the results of cross-case comparison.

The qualitative component of this study was limited by the relatively low number of stakeholders, even though with substantial professional experience. Their insights are subjective and based on discussions of specific projects. Therefore, the qualitative findings should not be interpreted in isolation but should

be complemented by a broader set of national but also cross-context level studies with a similar scope.

Despite the limitations, combining LCAs with stakeholder interviews provided valuable contextual insights and helped address the gap of LCA through the interpretation of practitioners' experience.

This mixed approach offers a more holistic understanding of why certain solutions succeed in practice and why the adoption patterns differ depending on context. Although this research covers only three case studies, it contributes to the experiential knowledge, which is crucial as the construction sector is ultimately shaped by human decisions.

6. Conclusion

This chapter outlines the broader implications of the study's findings for research, policy and professional practice and concludes with the general synthesis summarising the findings from this study.

6.1 Implications for future work

The following sections discuss how the insights from this study can inform future research development, the implementation of policy frameworks and more effective professional communication.

6.1.1 Implications for research

While quantitative studies are essential for assessing performance and enabling comparison through absolute values, qualitative approaches provide insight into the human factors and decision-making processes that determine whether sustainable solutions are implemented in practice. Combining both approaches offers a more holistic understanding and helps identify key barriers and critical points in the process where interventions have the most potential. Collaborative work between researchers and practitioners could further enhance LCA usability and promote its integration into everyday practice.

To build on this study's findings, future research should employ mixed-method approaches and create larger datasets to explore clear patterns between quantitative and qualitative evidence. Such empirical evidence would help to determine whether the observed differences, both quantitative and qualitative, arise from LCA variations or truly distinct environmental impacts.

Further investigations should also examine how the identified barriers and enablers evolve under changing national conditions. The share of renewables in the national energy mixes (see Section 2.7.3) and the trends in emissions (see Section 2.7.4) may influence the future potential of low-emission buildings.

6.1.2 Implications for policy

Collaboration and communication between policymakers, designers and developers are crucial when developing policies that support the implementation of energy-efficient and low-carbon buildings. Such communication should bridge not only disciplinary silos but also the institutional levels between EU, national and local authorities.

EU-level regulations and their national transpositions should be clear, functional and supportive in prac-

tice, promoting change rather than creating administrative complexity. Likewise, local regulations should be developed in consultation with professionals from the sector to ensure that specific requirements do not unintentionally complicate or delay – legally, technically or financially – the delivery of sustainable buildings.

Supporting collaborative procurement models, such as IPD, at the policy level could further facilitate knowledge exchange and the delivery of ambitious low-carbon projects.

Continuous harmonisation of LCA interpretation and reporting – especially in light of the 2024 EPBD recast – is essential for clear and transparent results comparability. At the same time, LCA methodologies should remain flexible enough to reflect national energy mixes, contextual factors and project scales.

6.1.3 Implications for practice

From a market perspective, progress requires raising awareness and knowledge among the general public, clients and homeowners. Developers and designers should therefore adopt a role that extends beyond their technical expertise, providing guidance and advocacy for more sustainable homes and other building typologies.

6.2 Synthesis of findings

This study shows that the success of low-carbon, high-efficiency buildings depends not only on climatic and technological conditions but equally on economic feasibility, construction practices, awareness, collaboration and enabling regulatory frameworks.

The comparison of three distinct national contexts shows that most high-efficiency solutions are technically transferable. However, their transferability relies less on technical capacity and more on systematic and institutional readiness. While context does not limit the technical feasibility, it influences motivation, costs and design priorities. Strengthening knowledge exchange among policymakers, professionals and end-users could accelerate the adoption and impact of energy-efficient, low-carbon construction across Europe.

Following these general insights, the next section directly addresses and summarises the three research questions defined in this dissertation.

This study aimed to address three research questions concerning the technical, contextual and transferability aspects of low-emission building solutions.

Regarding the first research question (RQ1), the findings show that the set of passive and active solutions is largely similar across all three case studies, but the extent of their application, the motivations behind their implementation and the factors influencing their adoption differ.

The second research question (RQ2) revealed that economic factors – closely linked to the risk of innovative or not yet established solutions – strongly shape the adopted measures. These risks can be mitigated through early-stage collaboration across stakeholders and by providing demonstration examples. Ownership structures influence the motivation for implementation and may determine which stages of the building life cycle are prioritised. Legislative frameworks establish common objectives, yet effective communication both across tiers and between institutional levels is needed to support broader adoption. Wider uptake and market motivations also depend on increasing public awareness – clients are unlikely to demand energy-efficient or low-carbon solutions if they are not aware of their feasibility and benefits – and on strong professional guidance. The main barriers are not climatic or technical, but economic, regulatory and informational. The LCA analysis further revealed that the benefits of studied strategies, particularly early-stage optimisation measures (e.g. material choice) are strongly dependent on the contextual aspects, such as building typology and electricity mix.

Findings related to the third research question (RQ3) indicate that the solutions used are generally transferable between the studied contexts, and therefore likely beyond them as well, although the factors influencing adoption will differ. All three research questions were addressed and the findings can contribute to the understanding of contextual barriers and enablers that can accelerate the wider adoption of low-emission building practices.

Bibliography

International Energy Agency, International Renewable Energy Agency, and UN Climate Change High-Level Champions (2023) *Breakthrough Agenda Report 2023*. Technical report, IEA, Paris. URL https://www.iea.org/reports/breakthrough-agenda-report-2023.

European Parliament and Council of the European Union (2021) *Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law')*. URL http://data.europa.eu/eli/reg/2021/1119/oj/eng. Legislative Body: CONSIL, EP, (Accessed: 13 March 2025).

European Parliament and Council of the European Union (2010a) *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)*. URL http://data.europa.eu/eli/dir/2010/31/oj/eng. (Accessed: 06 March 2025).

European Parliament and Council of the European Union (2024) *Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast) (Text with EEA relevance)*. Technical report. URL https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng. Doc ID: 32024L1275 Doc Sector: 3 Doc Title: Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast) (Text with EEA relevance) Doc Type: L Usr_lan: en.

Norwegian Ministry of Foreign Affairs (2022) *The EEA Agreement*. URL https://www.norway.no/en/missions/eu/areas-of-cooperation/the-eea-agreement/. (Accessed: 25 March 2025).

Maduta, C. and D'Agostino, D. (2024) Readiness of Zero-Emission Buildings (ZEBs) implementation in the European Union. *E3S Web of Conferences*, 523:04009. ISSN 2267-1242. doi: 10.1051/e3sconf/202452304009. URL https://www.e3s-conferences.org/articles/e3sconf/abs/2024/53/e3sconf_aicarr2024_04009/e3sconf_aicarr2024_04009.html. Publisher: EDP Sciences.

IEA EBC (2025a) *IEA EBC || Annex 89 || Ways to Implement Net-zero Whole Life Carbon Buildings || IEA EBC || Annex 89*. URL https://annex89.iea-ebc.org/. (Accessed: 04 March 2025).

IEA EBC (2025b) *International Energy Agency (IEA) Energy in Buildings and Communities (EBC)*. URL https://www.iea-ebc.org/. (Accessed: 25 October 2025).

United Nations (2025) *The Paris Agreement | United Nations*. URL https://www.un.org/en/climatechange/paris-agreement. (Accessed: 06 March 2025).

IEA EBC (2025c) *Subtasks || IEA EBC || Annex 89*. URL https://annex89.iea-ebc.org/subtasks. (Accessed: 04 March 2025).

Lou, H.-L. and Hsieh, S.-H. (2024) Towards Zero: A Review on Strategies in Achieving Net-Zero-Energy and Net-Zero-Carbon Buildings. *Sustainability*, 16:4735. doi: 10.3390/su16114735.

Tirelli, D. and Besana, D. (2023) Moving toward Net Zero Carbon Buildings to Face Global Warming: A Narrative Review. *Buildings*, 13(3):684. ISSN 2075-5309. doi: 10.3390/buildings13030684. URL https://www.mdpi.com/2075-5309/13/3/684. Number: 3 Publisher: Multidisciplinary Digital Publishing Institute.

Besana, D. and Tirelli, D. (2022) Reuse and Retrofitting Strategies for a Net Zero Carbon Building in Milan: An Analytic Evaluation. *Sustainability*, 14(23):16115. ISSN 2071-1050. doi: 10.3390/su142316115. URL https://www.mdpi.com/2071-1050/14/23/16115. Number: 23 Publisher: Multidisciplinary Digital Publishing Institute.

Ohene, E., Chan, A. P. C., and Darko, A. (2022) Prioritizing barriers and developing mitigation strategies toward net-zero carbon building sector. *Building and Environment*, 223:109437. ISSN 0360-1323. doi: 10.1016/j.buildenv.2022.109437. URL https://www.sciencedirect.com/science/article/pii/S0360132322006680.

Fufa, S., Schlanbusch, R., Andresen, I., Kjendseth Wiik, M., and Sørnes, K. (2016) *A Norwegian ZEB Definition Guideline*. doi: 10.13140/RG.2.2.26443.80162.

Ahmed, A., Ge, T., Peng, J., Yan, W.-C., Tee, B. T., and You, S. (2022) Assessment of the renewable energy generation towards net-zero energy buildings: A review. *Energy and Buildings*, 256:111755. ISSN 0378-7788. doi: 10.1016/j.enbuild.2021.111755. URL https://www.sciencedirect.com/science/article/pii/S0378778821010392.

Ürge Vorsatz, D., Khosla, R., Bernhardt, R., Chan, Y., Verez, D., Hu, S., and Cabeza, L. F. (2020) *(PDF) Advances Toward a Net-Zero Global Building Sector*. URL https://www.researchgate.net/publication/344049062_Advances_Toward_a_Net-Zero_Global_Building_Sector. (Accessed: 09 April 2025).

Oliveira Panao, M. J. N. and Gonçalves, H. J. P. (2011) Solar XXI building: Proof of concept or a concept to be proved? *Renewable Energy*, 36(10):2703–2710. ISSN 0960-1481. doi: 10.1016/j.renene.2011.03.002. URL https://www.sciencedirect.com/science/article/pii/S0960148111001169.

Lu, Y., Wang, S., and Shan, K. (2015) Design optimization and optimal control of grid-connected and standalone nearly/net zero energy buildings. *Applied Energy*, 155:463–477. ISSN 0306-2619. doi: 10.1016/j.apenergy.2015.06.007. URL https://www.sciencedirect.com/science/article/pii/S0306261915007655.

Falana, J., Osei-Kyei, R., and Tam, V. W. (2024) Towards achieving a net zero carbon building: A review of key stakeholders and their roles in net zero carbon building whole life cycle. *Journal of Building Engineering*, 82:108223. ISSN 2352-7102. doi: 10.1016/j.jobe.2023.108223. URL https://www.sciencedirect.com/science/article/pii/S2352710223024038.

Pannier, M.-L., Lemoine, C., Amiel, M., Boileau, H., Buhé, C., and Raymond, R. (2021) Multidisciplinary post-occupancy evaluation of a multifamily house: An example linking sociological, energy and LCA studies. *Journal of Building Engineering*, 37:102139. ISSN 2352-7102. doi: 10.1016/j.jobe.2020. 102139. URL https://www.sciencedirect.com/science/article/pii/S2352710220337712.

Moum, A., Hauge, , and Thomsen, J. (2017) *Four Norwegian Zero Emission Pilot Buildings – Building Process and User Evaluation*.

Morris, P., Vine, D., and Buys, L. (2016) Residential consumer perspectives of effective peak electricity demand reduction interventions as an approach for low carbon communities. *AIMS Energy*, 4:536–556. doi: 10.3934/energy.2016.3.536.

Menconi, M., Painting, N., and Piroozfar, P. (2018) *A Future-Proof Cultural Heritage: A Holistic Mixed Methods Approach*.

Alejandrino, C., Mercante, I., and Bovea, M. D. (2021) Life cycle sustainability assessment: Lessons learned from case studies. *Environmental Impact Assessment Review*, 87:106517. ISSN 0195-9255. doi: 10.1016/j.eiar.2020.106517. URL https://www.sciencedirect.com/science/article/pii/S0195925520307952.

Sonetti, G. and Lombardi, P. (2020) Multi-criteria Decision Analysis of a Building Element Integrating Energy Use, Environmental, Economic and Aesthetic Parameters in Its Life Cycle. *Green Energy and Technology Values and Functions for Future Cities*. doi: 10.1007/978-3-030-23786-8. URL https://www.academia.edu/40912874/Multi_criteria_Decision_Analysis_of_a_Building_Element_Integrating_Energy_Use_Environmental_Economic_and_Aesthetic_Parameters_in_Its_Life_Cycle.

Lützkendorf, T., Foliente, G., Balouktsi, M., and Wiberg, A. H. (2014) Net-zero buildings: incorporating embodied impacts. *Building Research & Information*, 43(1):62. ISSN 0961-3218. URL https://www.academia.edu/9772639/Net_zero_buildings_incorporating_embodied_impacts.

Panagiotidou, M. and Fuller, R. J. (2013) Progress in ZEBs—A review of definitions, policies and construction activity. *Energy Policy*, 62:196–206. ISSN 0301-4215. doi: 10.1016/j.enpol.2013.06.099. URL https://www.sciencedirect.com/science/article/pii/S030142151300606X.

Wells, L., Rismanchi, B., and Aye, L. (2018) A review of Net Zero Energy Buildings with reflections on the Australian context. *Energy and Buildings*, 158:616–628. ISSN 0378-7788. doi: 10.1016/j.enbuild. 2017.10.055. URL https://www.sciencedirect.com/science/article/pii/S037877881733445X.

Good, C., Wiberg, A., Kristjansdottir, T., Georges, L., and Hestnes, A. (2014) *A comparative study of different PV installations for a Norwegian net zero emission building concept*. doi: 10.18086/eurosun.2014.20.03. URL https://www.researchgate.net/publication/283295719_A_comparative_study_of_different_PV_installations_for_a_Norwegian_net_zero_emission_building_concept.

Sartori, I., Napolitano, A., and Voss, K. (2012) Net zero energy buildings: A consistent definition framework. *Energy and Buildings*, 48:220–232. ISSN 0378-7788. doi: 10.1016/j.enbuild.2012.01.032. URL https://www.sciencedirect.com/science/article/pii/S0378778812000497.

Bhavsar, R., Cupido, A., and Arriaga, M. (2020) MOHAWK COLLEGE'S NET ZERO ENERGY AND ZERO CARBON BUILDING—A LIVING LAB FOR HIGH EFFICIENCY AND RENEWABLE ENERGY TECHNOLOGIES IN BUILDINGS. *Journal of Green Building*, 15:185–214. doi: 10.3992/1943-4618. 15.1.185.

Moghaddasi, H., Culp, C., Vanegas, J., and Ehsani, M. (2021) Net Zero Energy Buildings: Variations, Clarifications, and Requirements in Response to the Paris Agreement. *Energies*, 14:21. doi: 10.3390/ en14133760. URL https://www.researchgate.net/publication/352690702_Net_Zero_Energy_Buildings_ Variations_Clarifications_and_Requirements_in_Response_to_the_Paris_Agreement.

International Organization for Standardization (2006a) *ISO 14040:2006 – Environmental management – Life cycle assessment – Principles and framework*. Technical report, ISO, Geneva, Switzerland. URL https://www.iso.org/standard/37456.html.

International Organization for Standardization (2006b) *ISO 14044:2006 – Environmental management – Life cycle assessment – Requirements and guidelines*. Technical report, ISO, Geneva, Switzerland. URL https://www.iso.org/standard/38498.html.

Pan, W. and Pan, M. (2021) Drivers, barriers and strategies for zero carbon buildings in high-rise high-density cities. *Energy and Buildings*, 242:110970. ISSN 0378-7788. doi: 10.1016/j.enbuild.2021. 110970. URL https://www.sciencedirect.com/science/article/pii/S0378778821002541.

Economidou, M., Todeschi, V., Bertoldi, P., D'Agostino, D., Zangheri, P., and Castellazzi, L. (2020) Review of 50years of EU energy efficiency policies for buildings. *Energy and Buildings*, 225:110322. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2020.110322. URL https://www.sciencedirect. com/science/article/pii/S0378778820317229.

Fragoso, R. and Baptista, N. (2021) *Portugal country report 2020 incl. KI&Ds*. URL https://www.ca-epbd. eu/outputs-archive/2021/portugal-incl-kiandds-2020. Legal body: Ministry of Industry and Trade...is that an author?, (Accessed: 19 March 2025).

Brekke, T., Isachsen, O. K., and Marton, I. (2021) *Norway country report 2020 incl. KI&Ds (Key Indicators and Desicsions)*. URL https://www.ca-epbd.eu/outputs-archive/2021/norway-incl-kiandds-2020. (Accessed: 12 March 2025).

Svoboda, V. (2021) *Czech Republic country report 2020 incl. KI&Ds*. URL https://www.ca-epbd.eu/ outputs-archive/2021/czech-republic-incl-kiandds-2020. (Accessed: 18 March 2025).

Papadopoulos, A. (2007) Energy cost and its impact on regulating building energy behaviour. *Advances in Building Energy Research*, 1:105–121. doi: 10.1080/17512549.2007.9687271.

R.S. Axelrod (1992) Scopus preview - Scopus - Document details - Reconciling energy use with environmental protection in the European Community. *International Environmental Affairs*, 4(3):185–202. URL https://www.scopus.com/record/display.uri?eid=2-s2.0-0027065797&origin=inward&txGid= 6418c77605b3a32edc5028c7c2dc8a90.

European Parliament and Council of the European Union (2002) *Directive - 2002/91 - EN - EUR-Lex*. URL https://eur-lex.europa.eu/eli/dir/2002/91/oj/eng. Doc ID: 32002L0091 Doc Sector: 3 Doc Title: Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings Doc Type: L Usr_lan: en, (Accessed: 21 May 2025).

European Parliament and Council of the European Union (2010b) *Directive - 2010/31 - EN - EUR-Lex*. URL https://eur-lex.europa.eu/eli/dir/2010/31/oj/eng. Doc ID: 32010L0031 Doc Sector: 3 Doc Title: Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast) Doc Type: L Usr_lan: en, (Accessed: 21 May 2025).

European Commission (2016) *Commission Recommendation (EU) 2016/1318 of 29 July 2016 on guidelines for the promotion of nearly zero-energy buildings and best practices to ensure that, by 2020, all new buildings are nearly zero-energy buildings*. Technical report. URL http://data.europa.eu/eli/reco/2016/1318/oj/eng. Code Number: 208 Code: OJ L Legislative Body: COM.

BPIE - Buildings Performance Institute Europe (2021) *Nearly Zero: A review of EU Member State implementation of new build requirements: BPIE - Buildings Performance Institute Europe*. Technical report. URL https://www.bpie.eu/publication/nearly-zero-a-review-of-eu-member-state-implementation-of-new-build-requirements/.

European Parliament and Council of the European Union (2018) *Directive - 2018/844 - EN - EUR-Lex*. URL https://eur-lex.europa.eu/eli/dir/2018/844/oj/eng. Doc ID: 32018L0844 Doc Sector: 3 Doc Title: Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency (Text with EEA relevance) Doc Type: L Usr_lan: en, (Accessed: 21 May 2025).

Europa (2025) *EU countries | European Union*. URL https://european-union.europa.eu/principles-countries-history/eu-countries_en. (Accessed: 04 April 2025).

Concerted Action EPBD (2025) *Norway*. URL https://www.ca-epbd.eu/countries/norway. (Accessed: 05 June 2025).

Nykamp, H. (2020) Policy mix for a transition to sustainability: Green buildings in Norway. *Sustainability (Switzerland)*, 12(2). doi: 10.3390/su12020446.

Kubečková, D. and Vrbová, M. (2021) Historical Development of Thermal Protection of Prefab Residential Housing and Its Future, an Example of the Czech Republic. *Energies*, 14:2623. doi: 10.3390/en14092623. URL https://www.researchgate.net/publication/351474918_Historical_Development_of_Thermal_Protection_of_Prefab_Residential_Housing_and_Its_Future_an_Example_of_the_Czech_Republic.

Pompl, D. (2017) Vývoj tepelně-technických vlastností budov a zateplovacích systémů. URL https://dspace.cvut.cz/handle/10467/70871. Accepted: 2017-06-25T16:00:37Z Publisher: České vysoké učení technické v Praze. Výpočetní a informační centrum.

Pejter, J. and Gebauer, P. (2011) *Implementation of the EPBD in the Czech Republic – Status in November 2010*. URL https://build-up.ec.europa.eu/sites/default/files/Czech_Republic.pdf. (Accessed: 28 May 2025).

Ministerstvo průmyslu a obchodu (2024) *Vyhláška č. 222/2024 Sb., kterou se mění vyhláška č. 264/2020 Sb., o energetické náročnosti budov*. URL https://www.e-sbirka.cz/sb/2024/222?zalozka=text. (Accessed: 22 May 2025).

Hudcová, L. (2009) *Energetická náročnost budov: základní pojmy a platná legislativa*. EkoWATT, Praha. ISBN 978-80-87333-03-7. OCLC: 614284933.

Ambiente e Ação Climática e Infraestruturas e Habitação (2021) *Portaria n.º 138-I/2021*. Technical report. URL https://diariodarepublica.pt/dr/detalhe/portaria/138-i-2021-166296492.

Čejka, M. and Antonín, J. (2017) *Budovy s téměř nulovou spotřebou - porovnání energetických standardů*. URL https://stavba.tzb-info.cz/budovy-s-temer-nulovou-spotrebou-energie/15181-budovy-s-temer-nulovou-spotrebou-porovnani-energetickych-standardu. (Accessed: 20 November 2025).

Direktoratet for byggkvalitet (2017) *Byggteknisk forskrift (TEK17)*. Regulation, Direktoratet for byggkvalitet (DiBK). URL https://www.dibk.no/regelverk/byggteknisk-forskrift-tek17.

Guinee, J. B. (2002) Handbook on Life Cycle Assessment. An Operational Guide to the ISO Standards. *The International Journal of Life Cycle Assessment*, 7(5):311–313. ISSN 1614-7502. doi: 10.1007/BF02978897. URL https://doi.org/10.1007/BF02978897.

Nwodo, M. N. and Anumba, C. J. (2019) A review of life cycle assessment of buildings using a systematic approach. *Building and Environment*, 162:106290. ISSN 0360-1323. doi: 10.1016/j.buildenv.2019.106290. URL https://www.sciencedirect.com/science/article/pii/S0360132319305001.

Cristobal-Garcia, J., Pant, R., Reale, F., and Sala, S. (2016) *Life cycle assessment for the impact assessment of policies*. Publications Office of the European Union. ISBN 978-92-79-64813-7. URL https://data.europa.eu/doi/10.2788/318544.

Sala, S., Pant, R., Hauschild, M., and Pennington, D. (2012) Research Needs and Challenges from Science to Decision Support. Lesson Learnt from the Development of the International Reference Life Cycle Data System (ILCD) Recommendations for Life Cycle Impact Assessment. *Sustainability*, 4(7): 1412–1425. ISSN 2071-1050. doi: 10.3390/su4071412. URL https://www.mdpi.com/2071-1050/4/7/1412. Number: 7 Publisher: Molecular Diversity Preservation International.

IEA (no date) *Glossary*. URL https://www.iea.org/glossary. (Accessed: 28 May 2025).

Sala, S., Mathieux, F., and Pant, R. Life Cycle Assessment and Sustainability Supporting Decision Making by Business and Policy. pages 201–214. (2016). doi: 10.1002/9781118933916.ch13.

CEN (2012) *NS-EN 15978:2011*. URL https://online.standard.no/nb/ns-en-15978-2011. (Accessed: 28 May 2025).

Potrč Obrecht, T., Kunič, R., Jordan, S., and Legat, A. (2019) Roles of the reference service life (RSL) of buildings and the RSL of building components in the environmental impacts of buildings. *IOP Conference Series: Earth and Environmental Science*, 323:012146. doi: 10.1088/1755-1315/323/1/012146.

Passive House Institute (no date) *About Passive House - What is a Passive House?* URL https://passiv.de/en/02_informations/01_whatisapassivehouse/01_whatisapassivehouse.htm. tex.shortauthor: PHI, (Accessed: 28 April 2025).

Zavadskas, E. K., Antucheviciene, J., Kalibatas, D., and Kalibatiene, D. (2017) Achieving Nearly Zero-Energy Buildings by applying multi-attribute assessment. *Energy and Buildings*, 143:162–172. ISSN 0378-7788. doi: 10.1016/j.enbuild.2017.03.037. URL https://www.sciencedirect.com/science/article/pii/S0378778817303596.

Feist, W., Schnieders, J., Dorer, V., and Haas, A. (2005) Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. *Energy and Buildings*, 37(11):1186–1203. ISSN 0378-7788. doi: 10.1016/j.enbuild.2005.06.020. URL https://www.sciencedirect.com/science/article/pii/S0378778805001118.

Chastas, P., Theodosiou, T., and Bikas, D. (2016) Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. *Building and Environment*, 105:267–282. ISSN 0360-1323. doi: 10.1016/j.buildenv.2016.05.040. URL https://www.sciencedirect.com/science/article/pii/S0360132316301986.

Kristjansdottir, T., Fjeldheim, H., Selvig, E., Risholt, B., Time, B., Georges, L., Dokka, T., Bourelle, J., Bohne, R. A., and Cervenka, Z. (2014) *A Norwegian ZEB-definition embodied emission*. URL https://www.researchgate.net/publication/266858163_A_Norwegian_ZEB-definition_embodied_emission.

SINTEF (2014) *ZEB*. URL https://www.sintef.no/en/projects/2014/zeb/. (Accessed: 05 June 2025).

Dokka, T. H., Sartori, I., Thyholt, M., Lien, K., and Lindberg, K. B. (2013) *A Norwegian Zero Emission Building Definition*. URL http://www.zeb.no/index.php/en/conference-papers/item/454-a-norwegian-zero-emission-building-definition. (Accessed: 29 April 2025).

IEA (2020a) *Heating degree days in Portugal, 2000-2020*. URL https://www.iea.org/data-and-statistics/charts/heating-degree-days-in-portugal-2000-2020. (Accessed: 20 November 2025).

IEA (2020b) *Heating degree days in Norway, 2000-2020*. URL https://www.iea.org/data-and-statistics/charts/heating-degree-days-in-norway-2000-2020. (Accessed: 20 November 2025).

IEA (2020c) *Heating degree days in the Czech Republic, 2000-2020*. URL https://www.iea.org/data-and-statistics/charts/heating-degree-days-in-the-czech-republic-2000-2020. (Accessed: 20 November 2025).

IEA (2020d) *Cooling degree days in Portugal, 2000-2020*. URL https://www.iea.org/data-and-statistics/charts/cooling-degree-days-in-portugal-2000-2020. (Accessed: 20 November 2025).

IEA (2020e) *Cooling degree days in Norway, 2000-2020*. URL https://www.iea.org/data-and-statistics/charts/cooling-degree-days-in-norway-2000-2020. (Accessed: 20 November 2025).

IEA (2020f) *Cooling degree days in the Czech Republic, 2000-2020*. URL https://www.iea.org/data-and-statistics/charts/cooling-degree-days-in-the-czech-republic-2000-2020. (Accessed: 20 November 2025).

IEA (2025a) *Portugal - Countries & Regions*. URL https://www.iea.org/countries/portugal. (Accessed: 29 May 2025).

IEA (2025b) *Norway - Countries & Regions*. URL https://www.iea.org/countries/norway/energy-mix. (Accessed: 29 May 2025).

IEA (2025c) *Czechia - Countries & Regions*. URL https://www.iea.org/countries/czechia. (Accessed: 29 May 2025).

Insituto Nacional de Estatística (2022) *Statistics Portugal - Web Portal*. URL https://www.ine.pt/xportal/xmain?contexto=bd&indOcorrCod=0011542&selTab=tab2&xlang=en&xpgid=ine_indicadores&xpid=INE&utm_source=chatgpt.com. (Accessed: 28 October 2025).

Norwegian Ministry of Energy (2025) *Heat supply*. URL https://energifaktanorge.no/en/norsk-energiforsyning/varmeforsyning/. (Accessed: 28 October 2025).

Český Statistický Úřad (2021) *Rozdělení domácností podle paliv a energií používaných na vytápění*. URL https://csu.gov.cz/produkty/rozdeleni-domacnosti-podle-paliv-a-energii-pouzivanych-na-vytapeni. (Accessed: 28 October 2025).

Ministerstvo průmyslu a obchodu (2022) *Zpráva o vývoji energetiky v oblasti tepla za rok 2020*. Technical report, Ministerstvo průmyslu a obchodu. URL https://mpo.gov.cz/cz/energetika/statistika/elektrina-a-teplo/zprava-o-vyvoji-energetiky-v-oblasti-tepla-za-rok-2020--270246/.

IEA (2025d) *Buildings - Energy System*. URL https://www.iea.org/energy-system/buildings. (Accessed: 29 May 2025).

Flyvbjerg, B. (2006) Five Misunderstandings About Case-Study Research. *Qualitative Inquiry*, 12:219–245. doi: 10.1177/1077800405284363.

Passive House Buildings (no date) URL https://passivehouse-database.org/index.php?lang=en#d_2403. (Accessed: 29 October 2025).

NTNU and SINTEF (no date) *ZEB Labotratory: Project info*. URL https://zeblab.no/projectinfo. (Accessed: 08 May 2025).

m.c.herzog / visualis-images (2022) *Storgjev pris til ZEB-laboratoriet*. URL https://zeblab.no/news/2022/10/20/storgjev-pris-til-zeb-laboratoriet. (Accessed: 29 October 2025).

The Research Centre on Zero Emission Buildings (no date) *Test Cell Laboratory*. URL https://www.zeb. no/index.php/en/test-cell-laboratory. (Accessed: 08 May 2025).

SINTEF and NTNU (no date) *Innovations at the ZEB Laboratory*. URL https://static1.squarespace. com/static/5a156c44ccc5c5ef7b893553/t/6555e2de51da2513b4ff735d/1700127457334/ ZEB_innovasjonsbrosjyre_finale2021_EN_18nov.pdf. (Accessed: 13 August 2025).

Skanska Residential (no date) *Prémiové bydlení Praha 5 | DOK - Radlice*. URL https://residential. skanska.cz/prodej-bytu-praha-5/dok-radlice-drevak. (Accessed: 29 October 2025).

Hennink, M., Hutter, I., and Bailey, A. (2025) *Qualitative Research Methods*. URL https://uk.sagepub. com/en-gb/eur/qualitative-research-methods/book242878. (Accessed: 16 September 2025).

Dadzie, J., Runeson, G., Ding, G., and Bondinuba, F. (2018) Barriers to Adoption of Sustainable Technologies for Energy-Efficient Building Upgrade—Semi-Structured Interviews. *Buildings*, 8:57. doi: 10.3390/buildings8040057.

Bavaresco, M. V., D'Oca, S., Ghisi, E., and Lamberts, R. (2020) Methods used in social sciences that suit energy research: A literature review on qualitative methods to assess the human dimension of energy use in buildings. *Energy and Buildings*, 209:109702. ISSN 0378-7788. doi: 10.1016/j.enbuild. 2019.109702. URL https://www.sciencedirect.com/science/article/pii/S0378778819325599.

Busetto, L., Wick, W., and Gumbinger, C. (2020) How to use and assess qualitative research methods. *Neurological Research and Practice*, 2:14. doi: 10.1186/s42466-020-00059-z.

Denzin, N. K. and Lincoln, Y. S. (2011) *The SAGE Handbook of Qualitative Research*. SAGE. ISBN 978-1-4129-7417-2.

Sikt (no date) *About Sikt – Norwegian Agency for Shared Services in Education and Research*. URL https://sikt.no/en/about-sikt. (Accessed: 22 August 2025).

Mero-Jaffe, I. (2011) 'Is that what I Said?' Interview Transcript Approval by Participants: An Aspect of Ethics in Qualitative Research. *International Journal of Qualitative Methods*, 10. doi: 10.1177/ 160940691101000304.

Bailey, J. (2008) First steps in qualitative data analysis: Transcribing. *Family Practice*, 25. doi: 10.1093/ fampra/cmn003.

Oliver, D. G., Serovich, J. M., and Mason, T. L. (2005) Constraints and Opportunities with Interview Transcription: Towards Reflection in Qualitative Research. *Social forces; a scientific medium of social study and interpretation*, 84(2):1273–1289. ISSN 0037-7732. doi: 10.1353/sof.2006.0023. URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1400594/.

Fairclough, N. (1992) Discourse and social change. 22(3). ISSN 1469-8013, 0047-4045. doi: 10.1017/S0047404500017309. URL https://www.cambridge.org/core/journals/language-in-society/ article/abs/norman-fairclough-discourse-and-social-change-cambridge-polity-1992-pp-vii-259/ F603F3842426EFF10228310B55BA12D8.

Braun, V. and Clarke, V. (2006) Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3:77–101. doi: 10.1191/1478088706qp063oa.

Kuklík, P. and Gregorová, A. (2025) *Aktuální stav technické normalizace pro dřevostavby*. URL https://stavba.tzb-info.cz/drevostavby/28547-aktualni-stav-technicke-normalizace-pro-drevostavby. (Accessed: 16 October 2025).

Machado, N., Silvestre, J., and Bohne, R. A. (2025) Embodied GHG emissions of reinforced concrete and timber structures: Relevance, driving factors and target values. *Building and Environment*, 275: 112753. doi: 10.1016/j.buildenv.2025.112753.

Borovcová, D. (2023) *Výstavba bytů v rodinných domech v dlouhodobém horizontu*. URL https://statistikaamy.csu.gov.cz/vystavba-bytu-v-rodinnych-domech-v-dlouhodobem-horizontu. (Accessed: 21 October 2025).

Appendices

Appendix A: Information Letter

Do you want to participate in

Master's dissertation "Comparative study of low-emission building solutions: case studies from Norway, Portugal and Czechia and their transferability to other Climates"?

Purpose of the project

You are invited to participate in a project where the aim is to

- Collect data for the master's dissertation in Civil engineering "Comparative study of low-emission building solutions: case studies from Norway, Portugal and Czechia and their transferability to other Climates" in the framework of the International Energy Agency Energy in Buildings and Communities Programme (IEA EBC) project Annex 89, Subtask 4;
- Study three case study buildings: the ZEB Laboratory in Trondheim (Norway), the Rua do Mar family house in Ílhavo (Portugal), and a third building to be specified (Czechia) in terms of energy efficiency and carbon footprint;
- Investigate how, why and what decisions are made and what measures are applied to reduce whole life carbon in buildings and what are the real outcomes (performance, indoor environments, etc.);
- The data will be used primarily for the master's dissertation, but may also be shared, used, and potentially published in some work of the project Annex89.

Why are you being asked to participate?

You are being invited to participate because

- You have been involved in one or more stages of the building process of the selected building, or you are an end-user of the building;
- You were selected for this study because your insights are considered valuable to the scope of the master's dissertation and the IEA EBC Annex 89 project.

  Additional information:
- The contact with you was made either through the author's or supervisors' professional network, or via publicly available contact information.
- The estimated number of participants to be invited to take part in this study is expected to range from six to twenty.

Who is responsible for the research project?

Faculty of Engineering/Department of Civil and Environmental Engineering (NTNU) and Instituto Superior Técnico/Faculty of Civil Engineering (ULisboa) are responsible for the project.

Faculty of Engineering/Department of Civil and Environmental Engineering (NTNU) is responsible for the personal data processed in the project.

- The institution responsible for the processing of personal data is NTNU (Norwegian University of Science and Technology.

- The master's dissertation is conducted by the student at University of Lisbon (ULisboa - Instituto Superior Técnico) collaborating with NTNU, therefore the research will be conducted withing the guidelines of both of the institutions.

Participation is voluntary

There will be no negative consequences if you do not want to participate or if you later request to have your personal data deleted.

What does your participation entail?
- The data will be collected through the semi-structured interview.
- The interview will be centered around building and all its stages (planning, design, construction and use). It will involve questions regarding opinions and experiences with the processes, measures towards the high energy efficiency of the building, and other aspects (cultural, legislative, technical, etc.).
- The data collected includes information about your role in the project (e.g., architect, consultant, user, owner), opinions, reflections on challenges, cultural and regulatory contexts, and other factors that influenced the project outcomes and the choice of solutions that enabled for the building to perform in high efficiency standard.
- The interview will be audio recorded in case of "face to face" interview and video recorded in case of online interview through the Teams platform and automatically transcribed. For better transcription quality, additional transcription software may be used. The transcription software used will align with the NTNU regulation for the personal data collection.
- After the interview, you will receive the interview transcription for the revision, within 14 days, you can request your data to be deleted.

Brief information about data protection

We will only use data about you for the purposes described in this letter. We will process personal data confidentially and in accordance with data protection legislation. You can read more about privacy below*.

Sincerely,

Freja Nygaard Rasmussen   Veronika Wenkeová
(Researcher/supervisor)   (Student)

You can read more about data protection below.

READ MORE

Data protection - how we store and use your personal data
- The data provided by you will be available to the author of the master's dissertation (student) and both supervisors (at NTNU and the home university ULisboa) and may be made available to the team of Annex 89 project. If any of the members of the Annex89 team need to access any of the data, the access will be granted only with the permission of one of the supervisors;
- Your name and contact details will be replaced with a code that will be stored on a list of names separate from other data;
- The data will be stored on the encrypted drive;
- Your contribution will remain anonymous; however, to interpret the input, your role may be identified, which could make your identity apparent to some;
- The analysis of the results will be included in the dissertation and may be shared within the Annex89 team. It may be included in whole or part within a report to policy makers, as an official output of the Annex 89 Subtask 4.

What gives us the right to process data about you?

We process your information based on your consent.

On behalf of Faculty of Engineering/Department of Civil and Environmental Engineering, NTNU, the Data Protection Services at the Norwegian Agency for Shared Services in Education and Research (Sikt) have assessed that the processing of personal data in this project meets requirements in data protection legislation.

What happens to your personal data when the project ends?
The master's dissertation is expected to end by the end of 2025, however, the project Annex89 is expected to end by the end of 2027.

After the end of the Annnex89 project the collected data will be deleted. The analysis of the results will be included in the dissertation that may be publicly available online. It may be included in whole or partially within a report to policy makers, as an official output of the Annex 89 Subtask 4.

Your rights
As long as you can be identified in the collected data, you have the right to request access to the data we are processing about you, to request that the data is corrected or deleted. After the interview, you will receive the transcription for the revision, within 14 days, you can

request your data to be deleted. If you contact us regarding your rights, you will hear from us within 14 days. We will provide an explanation if we cannot identify you or if your rights cannot be exercised. You also have the right to lodge a complaint with the Data Protection Authority about how we are processing your data.

If you have questions or want to exercise your rights, please contact:
- Freja Nygaard Rasmussen, freja.n.rasmussen@ntnu.no
- Our Data Protection Officer: Thomas Ørnulf Helgesen, thomas.helgesen@ntnu.no

If you have questions about how Data Protection Services have assessed the project, you can contact them by email: personverntjenester@sikt.no, or by phone: 73 98 40 40.

Appendix B: Interview Guide

Introduction

Topic: Comparative study of low-emission building solutions: case studies from Norway, Portugal and Czechia and their transferability to other climates

This interview is made as a part of my master's dissertation which is conducted within the framework of the project "IEA EBC - Annex 89 - Ways to Implement netZ-WLC". Annex89 focuses on pathways and actions needed by various stakeholders and decision-makers to implement whole life cycle based net-zero GHG emissions from buildings in policy and practice.

In my dissertation I explore three case studies from different countries. I will examine each in terms of the technical solutions applied and their performance (through Life Cycle Assessment) and the point of view of the stakeholders involved with those buildings.

Participant consent information

By e-mail, you received the Information letter about the project, data processing and storage and your rights.

Let me summarize the information:

The information you provide may be used in my dissertation, either indirectly or as cited content, and potentially in the further work of Annex89. Your contribution will remain anonymous; however, to interpret the input, your role may be identified, which could make your identity apparent to some.

The interview will be recorded and transcribed from the recording and the transcript will be made available to you. You have the right to be withdrawn from the study or withdraw all or any parts of your input, throughout the interview or up to 14 days after receiving the interview transcript. The data you provide will be stored until the end of the Annex89 project, which is expected by the end of 2027.

With information provided in the information letter and this summary, do you consent to proceed with the interview and processing the data you provide?

Stakeholders interview

(Note: For the project in the design stage, questions will be adapted for the future expectations e.g., "What do you think will be the challenges?" etc.)

1. **Project Overview & Process**

   1.1. What was your role in the project and which stages were you involved in?

   1.2. What was the ambition for the project in terms of energy efficiency/ carbon footprint? What motivated this ambition? (comfort/ market - distinction from others to sell better/ energy savings/ green aim etc.)

   1.3. How was this ambition set in the project, what was the process? Who initiated or influenced it?

   1.4. What was the project timeline? Were there any key decisions towards the set ambition during different phases?

   1.5. What measures were implemented to achieve the level of the set ambition?

   1.6. Were any measures problematic to implement? Why?

   1.7. Did external factors (legislation, culture, climate, available technology etc.) influence the project? Were any planned measures dropped along the way because of those factors?

   1.8. What were the barriers in implementing the efficiency measures (e.g., budget, technical issues, resistance from contractors or users)? (If not answered within the previous question)

   1.9. Are there some common misconceptions among the general public when speaking of ZEB buildings/ Passive houses (e.g., related to comfort, cost, durability)?

2. **Reflection on the project**

   2.1. What is it like to live in/use the energy efficient/(net) ZEB building? Looking back at the time that have passed since the building was built, does the building perform as expected, or have there been any surprises?

2.2. What are the lessons learned? What measures would you implement again in future projects and what measures you wouldn't?

2.3. Since the project, how have the ambitions (energy efficiency/carbon footprint) in the construction sector evolved? Where do you think these ambitions should be today in terms of building standards and practices?

2.4. What was your experience with support for implementing energy-efficient/(net) ZEB building (e.g., public initiatives or policies)? How has the sector knowledge, awareness, and mainstream concepts changed since then?

Appendix C: Rua do Mar Family house – LCA summaries

Table C.1: LCA summary – GWP Total.

Scope

Databases Used	EPDs
Lifetime of Construction (years)	50
Heated floor area – BRA (sqm)	223.7
Functional Unit	1sqm over a 50 yr lifetime
Building Site	Ílhavo, Portugal

Building Element	A1 - A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	kgCO$_{2eq}$	kgCO$_{2eq}$/yr	kgCO$_{2eq}$/m^2	kgCO$_{2eq}$/m^2/yr	Contribution	Total FU /category	Tot% /category	D
Building — Building, general																				7,94	62,55%	
Foundations	4266	50	19	-290	0	0	0	0	0	0	129	222	143	0	4539	91	20,3	0,41	3,20 %			-245
Superstructure	22917	494	43	-652	0	0	0	0	0	0	698	720	503	2	24725	495	110,5	2,21	17,41 %			-1009
Outer walls	7564	69	118	0	0	0	0	0	0	0	93	134	1108	52	9139	183	40,9	0,82	6,43 %			-414
Inner walls	3151	39	275	0	0	0	0	0	0	0	0	121	18	51	3655	73	16,3	0,33	2,57 %			-87
Flooring	1229	26	316	0	101	0	2573	0	0	0	0	20	1760	9	6034	121	27,0	0,54	4,25 %			-4154
Roof	5184	174	41	-151	0	0	0	0	0	0	188	165	1265	26	6892	138	30,8	0,62	4,85 %			-501
Paints, claddings, finishes and other	9556	114	367	0	5	0	2934	0	0	0	19	156	272	195	13617	272	60,9	1,22	9,59 %			-4600
Grouts, screeds, mortars	1958	87	3	-40	0	0	0	0	0	0	29	83	17	31	2170	43	9,7	0,19	1,53 %			-43
Openings	9644	33	152	0	31	0	7857	0	74	0	0	56	160	56	18063	361	80,7	1,61	12,72 %			-6887
VVS — Heating, Ventilation and Sanitation, general																						
Heating and cooling (compact unit)	1600	181	0	0	0	0	1793	0	0	0	0	1	10	2	3587	72	16,0	0,32	2,53 %	0,32	2,53%	-712
Electric Pow — Electric Power, general																						
PV panels	1024	0	22	0	0	0	1069	0	0	0	0	0	23	0	2139	43	9,6	0,19	1,51 %			-331,2
Thermal solar panels	738	0	0	0	0	0	1793	0	0	0	0	1	10	2	2545	51	11,4	0,23	1,79 %	0,42	3,30%	-712,0
Construction		0	0	0											0,00	0,00	0,00	0,00	0,00%	0,00	0,00%	
Operation									44925						44925	898,49	200,83	4,02	31,63%	4,02	31,63%	-19695
kgCO$_{2eq}$	68830	1266	1358	-1132	137	0	18021	0	44999	0	1156	1679	5289	426	142029	2841	635	13	100%			-394
kgCO$_{2eq}$/yr	1377	25	27	-23	3	0	360	0	900	0	23	34	106	9								-394
kgCO$_{2eq}$/m^2	307,7	5,7	6,1	-5,1	0,6	0,0	80,6	0,0	201,2	0,0	5,2	7,5	23,6	1,9								-88,0
kgCO$_{2eq}$/m^2/yr	6,15	0,11	0,12	-0,10	0,01	0,00	1,61	0,00	4,02	0,00	0,10	0,15	0,47	0,04								-1,76
Contribution	48,5%	0,9%	1,0%	-0,8%	0,1%	0,0%	12,7%	0,0%	31,7%	0,0%	0,8%	1,2%	3,7%	0,3%								

M	C		O
7,76	0,23		4,02

ZEB-COM	Production	ZEB Balance
12,02	-0,49	11,53

Table C.2: LCA summary – GWP Fossil.

Scope

Databases Used	EPDs
Lifetime of Construction (years)	50
Heated floor area - BRA (sqm)	223,7
Functional Unit	1sqm over a 50 yr lifetime
Building Site	Ilhavo, Portugal

Building Element		A1 - A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	kgCO₂eq	kgCO₂eq /yr	kgCO₂eq /m²	kgCO₂eq /m²/yr	Contribution	TotalFU /category	Tot% /category	D
Building	Building, general																				8,03	63,54%	
	Foundations	4258	49	18	-290	0	0	0	0	0	0	129	222	128	0	4515	90	20,2	0,40	3,20 %			-245
	Superstructure	23763	464	40	-652	0	0	0	0	0	0	2048	920	420	8	27012	540	120,8	2,42	19,12 %			-960
	Outer walls	8422	69	31	0	0	0	0	0	0	0	93	130	1110	52	9907	198	44,3	0,89	7,01 %			-413
	Inner walls	2772	32	5	0	0	0	0	0	0	0	0	94	13	40	2957	59	13,2	0,26	2,09 %			-67
	Flooring	3646	26	113	0	43	0	2459	0	0	0	0	15	27	5	6333	127	28,3	0,57	4,48 %			-4145
	Roof	7400	360	40	-151	0	0	0	0	0	0	226	207	1245	27	9355	187	41,8	0,84	6,62 %			-525
	Paints, claddings, finishes and other	8728	114	89	0	0	0	40	0	0	0	15	89	144	97	9315	186	41,6	0,83	6,59 %			-2390
	Grouts, screeds, mortars	2089	87	4	-40	0	0	0	0	0	0	29	82	17	31	2300	46	10,3	0,21	1,63 %			-42
	Openings	9884	33	9	0	29	0	7818	0	74	0	6	60	92	63	18068	361	80,8	1,62	12,79 %			-6880
VVS	Heating, Ventilation and Sanitation, general																				0,32	2,52%	
	Heating and cooling (compact unit)	1590	181	0	0	0	0	1783	0	0	0	0	1	10	2	3567	71	15,9	0,32	2,52 %			-716
Electric Power	Electric Power, general																				16,92	2,58%	
	PV panels	1028	0	23	0	0	0	1073	0	0	0	0	0	22	0	2146	43	9,6	0,19	1,52 %			-325,4
	Thermal solar panels	739	0	0	0	0	0	749	0	0	0	0	1	8	1	1499	30	6,7	0,13	1,06 %			-1001
Construction			0	0												0,00	0,00	0,00	0,00	0,00 %	0,00	0,00%	
Operation										44302						44302	886,05	198,04	3,96	31,36 %	3,96	31,36%	-17710
	kgCO₂eq	74321	1414	372	-1132	71	0	13922	0	44376	0	2546	1821	3236	327	141275	2826	632	13	100%			-354
	kgCO₂eq/yr	1486	28	7	-23	1	0	278	0	888	0	51	36	65	7								
	kgCO₂eq/m²	332,2	6,3	1,7	-5,1	0,3	0,0	62,2	0,0	198,4	0,0	11,4	8,1	14,5	1,5								-79,2
	kgCO₂eq/m²/yr	6,64	0,13	0,03	-0,10	0,01	0,00	1,24	0,00	3,97	0,00	0,23	0,16	0,29	0,03								-1,58
	Contribution	52,6 %	1,0 %	0,3 %	-0,8 %	0,1 %	0,0 %	9,9 %	0,0 %	31,4 %	0,0 %	1,8 %	1,3 %	2,3 %	0,2 %								

M	C		O
7,89	0,16		3,97

ZEB-COM	Production	ZEB Balance
12,02	-0,49	11,53

Scope

Databases Used	EPDs
Lifetime of Construction (years)	50
Heated floor area - BRA (sqm)	223,7
Functional Unit	1sqm over a 50 yr lifetime
Building Site	Ílhavo, Portugal

Table C.3: LCA summary – GWP Biogenic.

Building Element	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	C3-balancing/C4 balancing	kgCO₂eq	kgCO₂eq/yr	kgCO₂eq/m²	kgCO₂eq/m³/yr	Contribution	Total FU/category	Tot%/category	D
Building																							
Building, general																					0,13	97,96%	
Foundations	13	0	1	0	0	0	0	0	0	0	0	0	16	0	0	29	0,6	0,13	0,00	1,90 %			0
Superstructure	-852	0	3	0	0	0	0	0	0	0	-11	0	82	0	946	169	3,4	0,76	0,02	11,09 %			46
Outer walls	-860	0	87	0	0	0	0	0	0	0	0	0	0	0	869	97	1,9	0,43	0,01	6,37 %			-1
Inner walls	-237	0	270	0	0	0	0	0	0	0	0	0	0	0	237	270	5,4	1,21	0,02	17,74 %			6
Flooring	-1911	0	67	0	0	0	111	0	0	0	0	0	1729	0	170	168	3,4	0,75	0,01	11,00 %			-3
Roof	-250	0	1	0	0	0	0	0	0	0	0	0	26	0	266	44	0,9	0,20	0,00	2,87 %			2
Paints, claddings, finishes and other	-270	0	133	0	0	0	2	0	0	0	0	0	123	86	144	218	4,4	0,97	0,02	14,28 %			8
Grouts, screeds, mortars	-178	0	1	0	0	0	0	0	0	0	0	0	0	8	179	10	0,2	0,05	0,00	0,67 %			0
Openings	51	0	142	0	0	0	41	0	0	0	6	4	67	3	174	488	9,8	2,18	0,04	32,04 %			-2
VVS																							
Heating, Ventilation and Sanitation, general																					0,00	1,20%	
Heating and cooling (compact unit)	9	0	0	0	0	0	9	0	0	0	0	0	0	0	0	18	0,4	0,08	0,00	1,20 %			3
Electric Power																					0,00	0,32%	
Electric Power, general																							
PV panels	-5	0	2	0	0	0	-1	0	0	0	0	0	1	2	6	5	0,1	0,02	0,00	0,32 %			-1,7
Thermal solar panels	-1	0	0	0	0	0	-2	0	0	0	0	0	0	0	3	0	0,0	0,00	0,00	0,00 %			-2
Construction			0													0,00	0,00	0,00	0,00	0,00 %	0,00	0,00%	
Operation			0						8							7,98	0,16	0,04	0,00	0,52 %	0,00	0,52%	
kgCO₂eq	-4493	1	708	0	0	0	160	0	8	0	-5	5	2044	100	2995	1523	30	7	0	100%			55
kgCO₂eq/yr	-90	0	14	0	0	0	3	0	0	0	0	0	41	2	60								1
kgCO₂eq/m²	-20,1	0,0	3,2	0,0	0,0	0,0	0,7	0,0	0,0	0,0	0,0	0,0	9,1	0,4	13,4								0,2
kgCO₂eq/m²/yr	-0,40	0,00	0,06	0,00	0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,18	0,01	0,27								0,00
Contribution	-295 %	0%	46 %	0%	0%	0%	11 %	0%	1 %	0%	0%	0%	134 %	6,6%	1,97								

M	C
-0,39	0,06

O
0,00

ZEB-COM	Production	ZEB Balance
-0,32	0,00	-0,32

Table C.4: LCA summary – GWP LULUC.

Scope

Databases Used	EPDs
Lifetime of Construction (years)	50
Heated floor area - BRA (sqm)	223,7
Functional Unit	1sqm over a 50 yr lifetime
Building Site	Ilhavo, Portugal

Building Element		A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	kgCO₂eq	kgCO₂eq/yr	kgCO₂eq/m²	kgCO₂eq/m²/yr	Contribution	Total FU/bygningsdel	Tot %/bygningsdel	D
Building	Building, general																				0,02	23,41%	
	Foundations	3	0	0	0	0	0	0	0	0	0	0	1	0	0	4	0	0,0	0,00	0,48 %			4
	Superstructure	14	0	0	0	0	0	0	0	0	0	2	2	1	0	18	0	0,1	0,00	2,27 %			18
	Outer walls	3	0	0	0	0	0	0	0	0	0	0	1	0	0	4	0	0,0	0,00	0,48 %			4
	Inner walls	1	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0	0,0	0,00	0,26 %			2
	Flooring	51	0	2	0	1	0	5	0	0	0	0	0	0	0	59	1	0,3	0,01	7,27 %			59
	Roof	4	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0,0	0,00	0,56 %			5
	Paints, claddings, finishes and other	5	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0,0	0,00	0,76 %			6
	Grouts, screeds, mortars	8	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0,0	0,00	1,01 %			8
	Openings	57	0	0	0	6	0	18	0	0	0	0	2	0	0	83	2	0,4	0,01	10,32 %			83
VVS	Heating, Ventilation and Sanitation, general																				0,00	0,20%	
	Heating and cooling (compact unit)	1	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0,0	0,00	0,20 %			0
Electric Power	Electric Power, general																				0,13	0,38%	
	PV panels	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0,0	0,00	0,25 %			-4,9
	Thermal solar panels	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0,0	0,00	0,13 %			-1

	A4	A5	B6	kgCO₂eq	kgCO₂eq/yr	kgCO₂eq/m²	kgCO₂eq/m²/yr	Contribution	Total FU/bygningsdel	Tot %/bygningsdel	D
Construction	0	0		0,00	0,00	0,00	0,00	0,00 %	0,00	0,00%	
Operation			614	614	12,29	2,75	0,05	76,01 %	0,05	76,01%	183
				808	16	4	0	100%			4

	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
kgCO₂eq	146	0	3	0	6	0	26	0	615	0	2	8	1	1
kgCO₂eq/yr	3	0	3	0	0	0	1	0	12	0	0	0	1	1
kgCO₂eq/m²	0,7	0,0	0,0	0,0	0,0	0,0	0,1	0,0	2,7	0,0	0,0	0,0	0,0	0,0
kgCO₂eq/m²/yr	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,05	0,00	0,00	0,00	0,00	0,00
Contribution	18,0%	0,0%	0,3%	0,0%	0,8%	0,0%	3,2%	0,0%	76,0%	0,0%	0,3%	1,0%	0,2%	0,1%

M	C	O
0,02	0,00	0,05

ZEB-COM	Production	ZEB Balance
0,07	0,00	0,07